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Test of Local Position Invariance at the Detector "Dulkyn-1"[1]

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Abstract—We present the results of testing local position invariance in a "null" gravitational red-shift experiment, carried out in the framework of the Research and Engineering Project "Dulkyn." The experimental data, collected during the five-month operation of a double-cavity laser system, where one cavity operated in the free generation mode while the frequency of the second cavity was stabilized by the nonlinear supernarrow absorption resonance of the methane molecule, confirmed the universality of the gravitational redshift law at a level of 0.9%.

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1. INTRODUCTION

General relativity (GR) is at present the commonly adopted metric theory of gravity and makes a basis for our knowledge of the space-time structure. Since 1919, GR has been verified at a more and more growing accuracy level, and by now it successfully explains all numerous experimental data [1]. However, the problem of quantum description of gravity is still remaining unsolved. The difficulties faced on the way of quantization of gravity as well as the anomalous behavior of the Universe, discovered in the late 90s and explained by the presence of a dark energy on the cosmological scale, show that the tensor structure underlying GR may require some change. The expected deflections from GR lead in some new theories to the necessity of violating the Einstein equivalence principle (EEP). Therefore testing the basic principles of GR becomes now a topical problem, and a confirmation or violation of these principles are equally important for the development of new ideas and theories aimed at widening the bounds of our understanding the structure of the Universe.

One of the consequences of the EEP leads to the existence of the gravitational redshift of spectral lines, which is equivalent to a dependence of the course of clocks on the local gravitational potential φ. According to the Local Position Invariance (LPI) principle, which is an inherent part of the EEP [2], the gravitational frequency shift in the course of clocks is universal and should not depend on the type of clocks used.

The LPI principle can be tested with the aid of experiments measuring the gravitational redshift effect, according to which, in weak gravitational fields ($\varphi/c^2 \ll 1$, c is the speed of light), the dependence of the frequency ν characterizing the course of any clock on the gravitational potential φ has the form $\nu = \nu_0(1 + \varphi/c^2)$, where ν_0 is the clock frequency in the absence of the gravitational field (the proper frequency). If one assumes a violation of the LPI, this dependence may be presented in the form [2]

$$\nu_A = \nu_0 \left[1 + (1 + \beta_A)\frac{\varphi}{c^2}\right],$$

where the dimensionless quantity β_A characterizes a deflection from the redshift law that follows from the EEP while the index A points at a possible dependence of the frequency ν_A on the specific type of clock used.

2. "NULL" GRAVITATIONAL REDSHIFT EXPERIMENT

One of the ways to check the LPI (the null gravitational redshift experiment [2]) is based on comparing the course of different clocks A and B placed at points with the same value of the gravitational potential, at time variations of the potential itself: $\varphi(t) = \varphi_0 +$

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$\Delta\varphi(t)$. In this case, a violation of the LPI principle will lead to a nonzero frequency difference

$$\nu_A - \nu_B = \nu_0(\beta_A - \beta_B)\frac{\Delta\varphi(t)}{c^2}. \quad (1)$$

A large number of experiments related to LPI tests according to Eq. (1), were conducted by comparing the atomic transitions frequencies of different elements at changes of the gravitational potential $\Delta\varphi(t)$, caused by the Earth's orbital motion around the Sun. The minimum upper bound on possible values of the quantity $(\beta_A - \beta_B)$ was obtained in this way in [3] by comparing the frequency variations of a hydrogen maser (H) and a caesium frequency standard (Cs): $|\beta_H - \beta_{Cs}| \leq 1.4 \times 10^{-6}$.

The gravitational potential change $\Delta\varphi(t)$ due to the Earth's orbital motion around the Sun along an ellipse with the eccentricity e is described by the expression [3]

$$\frac{\Delta\varphi(t)}{c^2} = e\frac{GM}{ac^2}\cos(E), \quad (2)$$

where G is the gravitational constant, M is the solar mass, a is the ellipse major semiaxis, and E is the eccentric anomaly determining the planet's position as an angle measured from the pericenter.

In [4, 5], a null redshift experiment was conducted by comparing an atomic transition frequency with the proper frequency of an electromagnetic resonator, i.e., the clocks compared had an entirely different physical nature.

In [4], as a result of measuring the frequency variations of a hydrogen maser (H) and a superconducting electromagnetic resonator, the following upper bound was obtained: $|\beta_{\text{res}} - \beta_H| \leq 1.7 \times 10^{-2}$. In [5], where frequency variations of an electronic transition in iodine molecules (I_2) were compared with those of the proper frequency of a cryogenic optical cavity, the established upper bound was $|\beta_{\text{res}} - \beta_{I_2}| \leq 4 \times 10^{-2}$. However, as pointed out in [3], the paper [5] wrongly used a double value of the factor at the cosine in Eq. (2), which led to a lower value of the upper bound, and with this correction this bound should read $|\beta_{\text{res}} - \beta_{I_2}| \leq 8 \times 10^{-2}$.

Experiments with clocks of different physical nature give an upper bound four orders of magnitude larger than the LPI tests using only atomic transition frequencies of different elements. Let us note that the experiments with clocks of *different* physical nature test the gravitational redshift universality in the most stringent manner because compared are *microscopic* (pointlike) quantum clocks whose frequency is determined by the fine structure constant with *macroscopic* (extended) clocks whose frequency is determined by the optical length of a cavity. In addition, in [6, 7] it was pointed out that these are just the experiments with clocks of different physical nature that should yield a maximally precise estimate of the quantity $(\beta_A - \beta_B)$ because there are several different approaches to obtaining a relativistic generalization of the classical theory of elasticity, which predict different results of the null redshift experiment. Thus a test of the LPI principle with clocks of different physical nature makes it possible to simultaneously make a selection among different ways of evaluating the relativistic response of an elastic medium to a variable gravitational field.

To test the LPI principle and the alternative ways of calculating the cavity length in a weak variable gravitational field, it has been suggested in [6, 7] to use a two-cavity laser system (TCLS) where the generation frequency of one of the cavities is locked to an atomic frequency standard ν_C while the second cavity remains in a free generation mode with the frequency ν_{res}. For a variation of the frequency difference of the TCLS cavities, $\Delta\nu(t) = \nu_{\text{res}} - \nu_C$, in a variable gravitational field, the following expression was obtained [6]:

$$\Delta\nu(t) = \nu_0(1-\xi)\frac{\Delta\varphi(t)}{c^2},$$

where the dimensionless phenomenological parameter ξ is determined by a solution of the elastodynamic problem of describing the evolution of the cavity geometric length $L(t) = L_0[1 + \xi\frac{\varphi(t)}{c^2}]$ in a variable gravitational field. As shown in [7], in determining $L(t)$ in a gravitational field with a slowly varying potential $\varphi(t)$, there are at least two alternative approaches in generalizing the classical theory of elasticity, and they predict different values of the phenomenological parameter ξ: $\xi = 1$ according to Maugin's approach [8] and $\xi = 0$ according to Weber's approach.

The idea of an LPI test put forward in [6, 7] has been realized at an experimental setup, the Dulkyn detector of the first level (Dulkyn-1). A detailed description of the structure and functional scheme of Dulkyn-1 and all technical characteristics of all its basic systems and blocks have been presented in [10].

The LPI principle was verified at the detector Dulkyn-1 in a null gravitational redshift experiment with the aid of a two-cavity laser system, where one cavity (the signal one) operated in a free generation mode while the frequency of the other (reference) cavity was stabilized by a supernarrow nonlinear absorption resonance of the methane molecule. The frequencies of these cavities were compared for five months subject to changes of the gravitational potential due to the Earth's orbital motion around the Sun. Thus this LPI testing experiment used

Table

Year	Upper bound	Reference
	Different atomic clocks	
1992	$\lvert\beta_{\rm H} - \beta_{\rm Cs}\rvert \leq 1 \times 10^{-4}$	[13]
1995	$\lvert\beta_{\rm Mg} - \beta_{\rm Cs}\rvert \leq 7 \times 10^{-4}$	[14]
2002	$\lvert\beta_{\rm H} - \beta_{\rm Cs}\rvert \leq 4.2 \times 10^{-5}$	[15]
2003	$\lvert\beta_{\rm H} - \beta_{\rm Cs}\rvert \leq 3.2 \times 10^{-5}$	[16]
2007	$\lvert\beta_{\rm H} - \beta_{\rm Cs}\rvert \leq 1.4 \times 10^{-6}$	[3]
	Clocks of different physical nature	
1983	$\lvert\beta_{\rm res} - \beta_{\rm H}\rvert \leq 1.7 \times 10^{-2}$	[4]
2002	$\lvert\beta_{\rm res} - \beta_{\rm I_2}\rvert \leq 8.0 \times 10^{-2}$	[5]
2009	$\lvert\beta_{\rm res} - \beta_{\rm CH_4}\rvert \leq 9.1 \times 10^{-3}$	Dulkyn-1 [11]
2010	$\lvert\beta_{\rm res} - \beta_{\rm H}\rvert \leq 4.5 \times 10^{-4}$	[12]

clocks of entirely different physical nature: a microscopic (pointlike) quantum clock, used for tuning the reference cavity of the TCLS, and a macroscopic (extended) clock whose frequency was determined by the optical length of the signal cavity.

The result of testing the LPI principle at Dylkyn-1 has been described in detail in [11], where Eq. (1) had the following form:

$$\nu_{\rm res} - \nu_{\rm CH_4} = \nu_0(\beta_{\rm res} - \beta_{\rm CH_4})\frac{\Delta\varphi(t)}{c^2},$$

where $\nu_{\rm res}$ is the generation frequency of the signal cavity, $\nu_{\rm CH_4} \cong \nu_0 \approx 8.848 \times 10^{13}$ Hz is the generation frequency of the reference cavity locked to the frequency of a precision single-block glass-ceramic He–Ne/CH_4 laser stabilized by a nonlinear supernarrow absorption resonance of the methane molecule (CH_4). Processing of the experimental data set has resulted in the following upper bound:

$$\lvert\beta_{\rm res} - \beta_{\rm CH_4}\rvert \leq 9.09 \times 10^{-3}. \qquad (3)$$

This result has improved the minimal (1.7% [4]) estimate in testing the LPI principle with clocks of different physical nature that existed by the experiment completion time. Three months later a group of French and Australian researchers obtained a more precise estimate, $\lvert\beta_{\rm res} - \beta_{\rm H}\rvert \leq 4.5 \times 10^{-4}$ by comparing for six years the frequency differences of a cryogenic sapphire oscillator and a hydrogen maser [12].

The following table, for comparison, puts together the main results obtained by different experimental groups in LPI testing by null gravitational red-shift experiments.

Let us stress once again that experiments with clocks of different physical nature give upper bounds by three or four orders of magnitude higher than LPI tests that compare only different atomic clocks. Nevertheless, in our opinion, a possible LPI violation, and consequently an EEP violation, may be most probably discovered just for *clocks of different physical nature*.

3. CONCLUSIONS

The quantity $\Delta\beta = \lvert\beta_{\rm res} - \beta_{\rm CH_4}\rvert$, characterizing a deflection from the LPI principle in a null gravitational redshift experiment, constrains the possible values of the parameter ξ that distinguishes different relativistic generalizations of elastodynamics, within $\lvert 1 - \xi\rvert \leq \Delta\beta$. Since (3) implies that $\lvert\beta_{\rm res} - \beta_{CH_4}\rvert$ does not exceed a value of the order of 0.009, the parameter ξ should be close to unity ($\xi = 1 \pm 0.009$). This means that Maugin's approach to relativistic generalization of the classical equation for wave propagation in an elastic medium, which corresponds to $\xi = 1$, agrees with the experimental results and with strict validity of the LPI principle.

It is planned for the nearest years to create the second-level detector Dulkyn-2, with a sensitivity higher than that of Dulkyn-1 by a few orders of magnitude. This should allow for a substantial improvement of the LPI tests for clocks of different physical nature. The sensitivity increase will be achieved by effectively suppressing the technological fluctuations of the difference frequency in the modified TCLS scheme [6], which also admits the opportunity of using the spontaneous emission correlation effect in order to substantially reduce the natural fluctuations of the difference frequency. A detailed description of the modified TCLS scheme and all auxiliary equipment of the second-level Dulkyn detector will be presented in a separate paper.

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