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Limits on the violation of g-universality with a Galileo-type experiment

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We present new results for a Galilean experiment using two masses of copper and tungsten in simultaneous free fall. The experiment searches for a possible difference in the free-fall acceleration Δg and it is sensitive to any composition-dependent interaction between the test masses and the earth, whose range exceeds 10 km. The results show no evidence for any composition-dependent gravity-like interaction within $\Delta g < 1$ μGal.

The GAL experiment is a free-fall experiment performed to search for a composition-dependent gravity-like "fifth force".

The experimental method, described elsewhere [1–3], aims to test the universality of the free-fall acceleration on the earth via a Galilean technique, using bodies with different nuclear composition.

This investigation has begun a few years ago, owing to the suggestion, forthcoming after a re-analysis of the Eötvös experiment results [4], that a "fifth force" produced by the baryonic charge could exist. This force would appear as an apparent violation of the universality of the free-fall acceleration for bodies having different nuclear composition.

The gravitational potential energy of two point-like masses m_1 and m_2 is modified, due to the presence of the fifth force, as follows,

$$V(r) = -Gm_1 m_2 [1 + \alpha \exp(-r/\lambda)]/r ,$$

where α is a material-dependent parameter which measures the deviation from the Newton law, and λ is the range of the force. Assuming the earth to be a homogeneous sphere of radius R_E, one has

$$\Delta g = (1 + R_E/\lambda) \exp(-R_E/\lambda) \times (\Delta\alpha) \varphi(R_E/\lambda) , \quad (1)$$

where $\varphi(x) = 3[x \cosh(x) - \sinh(x)]/x^3$. If $\lambda \ll R_E$, then

$$\frac{\Delta g}{g} \approx \frac{3}{2} \frac{\lambda}{R_E} \Delta\alpha .$$

A measurement of $\Delta g/g$ will, therefore, set limits on the product

$$\mathscr{K} \equiv \lambda \Delta\alpha . \quad (2)$$

Following the paper of Fischbach and co-workers, several experiments have been performed in order to test this suggestive hypothesis [5–10], but no violation of Newtonian gravity has been observed so far. There have also been theoretical suggestions that the fifth-force charge might be isospin, or some mixing of isospin, lepton number and baryon number [11,12]; but also these hypotheses were rejected, at least for ranges smaller than a few kilometers [13–15].

Torsion pendulum experiments using different sources, e.g. laboratory masses, the sun and the earth, have put very stringent limits on the possibility of the existence of the fifth force within different ranges of the distance [14]. However, since this technique is sensitive to the component of the fifth force normal to the earth gravity acceleration, in the range $10^4 \leqslant \lambda \leqslant 10^6$ m the measurements obtained with torsion pendula are affected by the underlying geological structure of the ground on the experiment site. On the other hand, the Galilean experiments, being sensitive to the fifth-force component parallel to the gravity force, though they have a slightly worse sensitivity, are much easier to interpret in this λ range.

Tests of the inverse square law of gravitational attraction have been performed also by composition-independent experiments, within the same range of distances (see ref. [16] and references therein), but no evidence for its violation was found.

The basic method used in GAL is to measure the angular acceleration $\dot{\omega}$ of a free falling disk, made of two half-disks of different materials, using a slightly modified Michelson interferometer, in which the two arms terminate in two corner-cube reflectors (CCR), mounted on the rim of the disk (see fig. 1). The two half-disks are held together via an aluminium disk

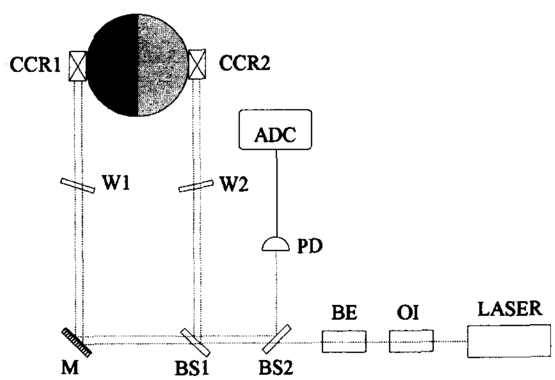

Fig. 1. Schematic view of the apparatus. DS is the disk, CCR are the corner-cube reflectors, W are optical windows, BS are beam splitters, M is a mirror, BE is a beam expander, OI is an optical isolator, PD are photodiodes and ADC is an analog-to-digital converter.

holder, which also houses eight CCR. We have performed two series of measurements, the former one [3] using a disk made of aluminium and copper, and the latter one with a disk of copper and tungsten.

The disk geometry has been chosen in order to minimize the effects due to gravity gradients. Moreover, the eight CCR give us the possibility of inverting the position of the half-disks with respect to the interferometric arms, by a 180° rotation of the disk assembly around its axis, without breaking the vacuum. The two half-disks have the same mass ($m=680.0\pm0.05$ g) and they have been manufactured in such a way as to have the gravity centers at the same distance from the disk axis ($b=2.921\pm0.002$ cm) and the same moments of inertia in the plane orthogonal to the disk axis ($\Delta J/J \leqslant 4\times10^{-4}$).

If there is a difference Δg in the free-fall acceleration of copper and tungsten, then the disk assembly experiences a torque

$$T=\tfrac{1}{2}(m_{\mathrm{Cu}}+m_{\mathrm{W}})b\Delta g$$

and, therefore, there is an angular acceleration of the disk assembly given by

$$\dot{\omega}=T/J_z\,,$$

where J_z is the moment of inertia of the disk assembly in the axis direction.

The measurement is performed by observing the interference on the photodiode PD during the free fall (see fig. 1). The light intensity is

$$I(t)=A\cos\phi(t)+B\,,$$

where A and B are the amplitude and the offset of the fringe, respectively, and $\phi(t)$ is the phase difference between the two optical paths, given by

$$\phi(t)=\phi_0+\frac{8\pi R}{\lambda}\sin(\omega_0 t+\tfrac{1}{2}\dot{\omega}t^2) \qquad (3)$$

$$\approx\phi_0+\frac{8\pi R}{\lambda}\omega_0 t+\frac{4\pi R}{\lambda}\dot{\omega}t^2\,, \qquad (4)$$

where λ is the light wavelength and $R=70$ mm is the distance between the disk axis and each CCR. The last term of eq. (4) which gives the frequency drift of the fringes, is proportional to the effect to be measured.

We have made 142 measurements with copper and tungsten and have obtained the following limit,

$$\Delta g/g_{\mathrm{Cu-W}} = (7.1 \pm 9.1) \times 10^{-10} . \quad (5)$$

The distribution of the residuals of the above measurements is shown in fig. 2.

The most serious source of systematic error in our measurement is the disk precession around the angular momentum. This precession simulates the presence of a disk angular acceleration $\dot{\Omega} = \omega_x \omega_y$, where ω_x and ω_y are the disk angular velocity components (at $t=0$) in the disk plane. This effect was monitored and corrected for the offline analysis by measuring, at the beginning of the free fall, the two angular velocities ω_x and ω_y with the help of a position sensitive photodiode detecting a laser beam reflected by a mirror placed on a side of the disk. Typical values were ω_x, $\omega_y \approx 1.5 \pm 0.1$ mrad/s, simulating disk angular accelerations $\dot{\Omega} \approx 2.2 \pm 0.3$ µrad/s^2, i.e. a $\Delta g/g \approx (400 \pm 60) \times 10^{-10}$.

A first set of measurements was taken using a homogeneous aluminium disk, to check the sensitivity of the apparatus and to look for possible spurious effects. With a total of 70 measurements, we obtained a $\Delta g/g = (3.2 \pm 9.5) \times 10^{-10}$.

According to eq. (2), the limit on the quantity $\mathscr{K}$ set by the experimental results (5) is

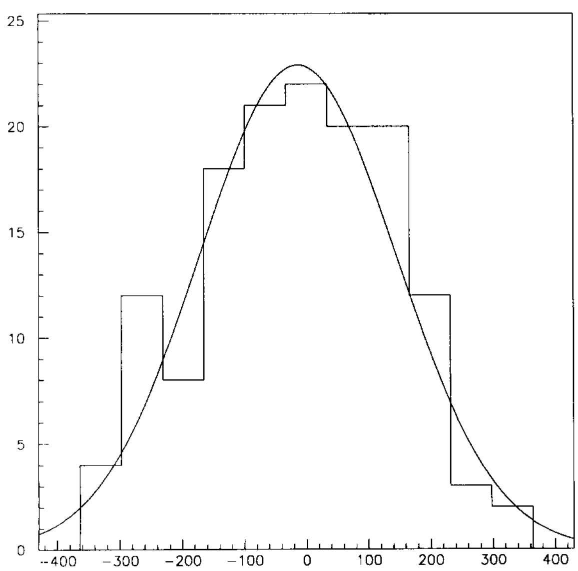

Fig. 2. Histogram of the residuals of the $\Delta g/g$ measurements for the W–Cu disk, in units of 10^{-10}, with the best fitting Gaussian curve superimposed on it.

Table 1
Results of the Galilean fifth-force experiments.

References	Compared materials	Δg (µGal)
present work	Cu–W	0.71 ± 0.91
[3]	Al–Cu	0.29 ± 0.72
[18]	Al–Cu	-0.13 ± 0.78
[18]	Al–Be	0.43 ± 1.23
[19]	Al–C	-0.18 ± 1.38
[17]	Cu–U	0.13 ± 0.5

$$|\mathscr{K}| \leqslant 0.63 \text{ cm (Cu–W)}$$

at a confidence level of 90%.

In table 1 we report the results obtained with the GAL experiment, together with the other free-fall experiments.

There is no evidence of any g-universality violation, at the level of µGal, at least with the Galileo-type experiment performed so far.

It is worthwhile recalling that, for ranges larger than the earth diameter, the results obtained with the torsion pendulum technique give no evidence for any g-universality violation [14] and set the following limits for Be–Al and Be–Au: $\Delta g/g = (0.5 \pm 1.3) \times 10^{-11}$ and $\Delta g/g = (0.2 \pm 1) \times 10^{-11}$, respectively.

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