Test of g Universality with a Galileo Type Experiment

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The results of an experiment searching for the difference Δg in the free-fall acceleration of aluminum and copper, in vacuum, obtained on the Earth in a differential Galileo type measurement are reported. Within the sensitivity of the measurement, $\Delta g/g = 7.2 \times 10^{-10}$; no g-universality violation has been observed.

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The GAL experiment [1, 2] is a modern version of the one that Galileo performed from the Pisa leaning tower, and it aims to test the universality of the free-fall acceleration g on the Earth with an accuracy of a few parts in 10^{-10}.

The interest in this matter was resurrected a few years ago with a reanalysis of the Eötvos experiment raising the question of the possible existence of a fifth force [3], which would manifest itself as an apparent violation of g universality. Because of this force, the potential energy of two pointlike masses m_1 and m_2 is modified as

$$V(r) = -Gm_1m_2[1 + \alpha \exp(-r/\lambda)]/r,$$

where α is material dependent and it measures the deviation from the Newton law, i.e., the fifth force contribution, and λ is the range of this force.

Several experiments with different techniques have been performed in order to verify the fifth force hypothesis, for different ranges [4–12]. Although at the beginning three experiments gave positive results in the $\lambda \leq 1$ km region [4, 7, 12], they were not confirmed by the successive generation of more sensitive experimental tests and one of them was retracted by the authors themselves [13]. At present, as Fischbach has affirmed in a recent review paper [14], no compelling evidence has emerged to indicate the presence of the fifth force. However, a direct measurement of Δg in a Galileo type experiment is the only way to verify the theory in the range between 10 km and the Earth radius [14]. Assuming the Earth as a homogeneous sphere of radius R_E, one has indeed

$$\frac{\Delta g}{g} \approx \frac{3}{2}\frac{\lambda}{R_E}\Delta\alpha \qquad (\lambda < R_E).$$

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

$$\mathcal{K} \equiv \lambda\,\Delta\alpha. \tag{1}$$

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. The angular motion of the disk around its axis is measured with the help of a modified Michelson interferometer, in which the two arms terminate in two corner-cube reflectors (CCR), mounted on the rim of the disk.

The disk assembly consists of an aluminum holder (see Fig. 1) which contains, in its central region, two half disks of aluminum and copper, respectively. The holder keeps the eight CCR used for the measurement at 70 mm from the disk axis.

The disk geometry has been chosen to minimize the effects due to local gravity gradients. We have mounted 8 CCR so as to have the possibility of inverting the position of the half disks with respect to the interferometric

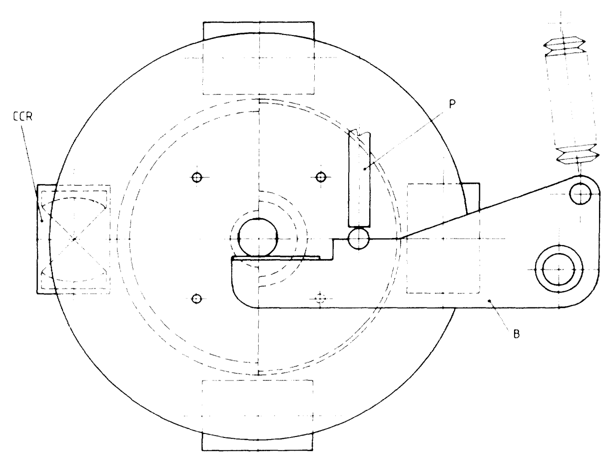

FIG. 1. View of the disk assembly and of the release mechanism. B and P indicate the mechanisms used to keep the disk in the upper position and to release it. CCR indicates corner-cube reflectors.

arms, by simply rotating the disk assembly 180° around its axis, without breaking the vacuum. The two half disks have been manufactured in such a way as to have (1) the same mass ($m_{\rm Al}$=346.8 g, $m_{\rm Cu}$=347.0 g); (2) the gravity centers symmetrically located with respect to the disk assembly at the same distance from the axis (b=2.412 ± 0.003 cm); and (3) the same moments of inertia in the plane orthogonal to the disk axis ($\Delta J/J < 10^{-3}$).

The experimental apparatus is schematically shown in Fig. 2. The light source is a frequency stabilized He-Ne laser (NL-1, from Newport). The disk is installed in a cylindrical stainless-steel vessel, 8 m in length, 270 mm in diameter, evacuated down to 4×10^{-3} Pa. To obtain the maximum optical contrast without changing the beam directions, we tilt the windows W3 and W4. All windows W1–W4, together with the beam splitter BS1, have been measured to have a prismaticity smaller than 2×10^{-6} rad.

A measurement cycle is initiated by mechanically releasing the carriage CR, which presents a housing for the disk axis. 10.3 ms after the carriage has started to free

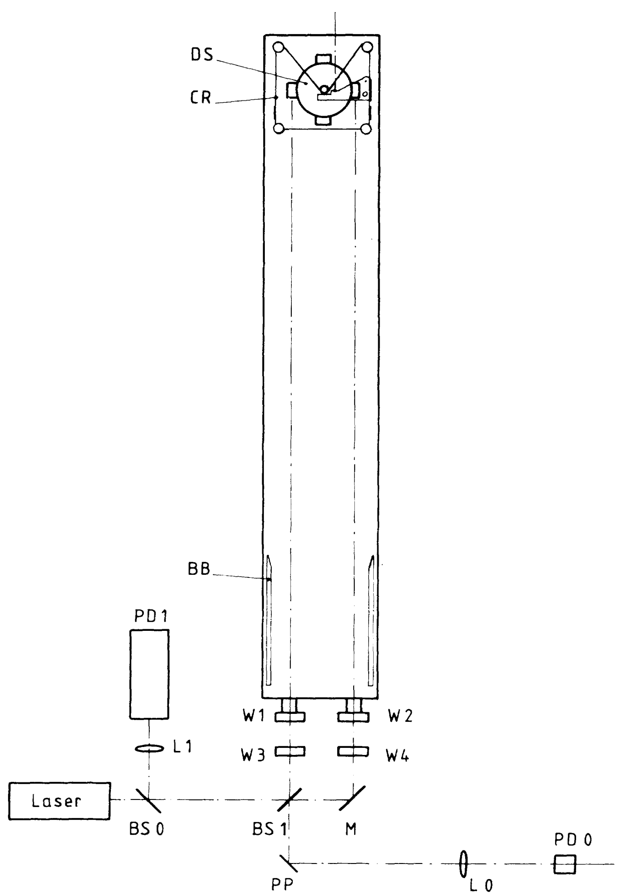

FIG. 2. Schematic view of the apparatus. DS is the disk, CR is the carriage, BB are the breaking bars, W are optical windows, BS are beam splitters, M is a mirror, L are lenses, PP is a pentaprism, and PD are photodiodes.

fall, the disk is also released. This time interval has been calibrated so as to guarantee no contact between the disk axis and the housing during the measurement. The carriage is guided by vertical rails on the first 30 cm of its path. To release the disk, we use a compressed air actuator, installed outside the vacuum vessel. After 4.2 m of free fall, a progressive deceleration is produced on the carriage by braking pads rubbing on spring-loaded stainless-steel bars. A soft landing of the disk on the carriage is obtained at the beginning of this braking by a suitable damping catch in the bottom of the axis housing. The whole assembly (disk+carriage) comes to rest in 1.5 m. A gear is used to pull the carriage with the disk on it to the top of the vacuum vessel for another measurement cycle.

During the disk free fall, the signal from the photodiode PD1 is sampled by a 14-bit analog-to-digital converter (SHA1144 + ADC1131K from Analog Devices) at a fixed, stable frequency of 50 kHz ($\delta\nu/\nu < 10^{-8}$), obtained from a thermally stabilized quartz oscillator (HP 3325A frequency synthesizer). The data are stored in a fast buffer memory (LeCroy MM8206A), which is read by a microcomputer at the end of each measurement and transferred to a host 8300 VAX computer, for off-line analysis.

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

$$T = (m_{\rm Al} + m_{\rm Cu})\frac{b\Delta g}{2}\ ,$$

and, therefore, there is an angular acceleration of the disk assembly $\dot\omega$ given by

$$\dot\omega = \frac{T}{J_0 + J_{\rm Al} + J_{\rm Cu}} = K\frac{\Delta g}{g},$$

where J_0, $J_{\rm Al}$, and $J_{\rm Cu}$ are the moments of inertia in the disk axis direction of the holder + CCR, of the aluminum half disk, and of the copper half disk, respectively.

The measurement of $\dot\omega$ is performed by observing, during the free fall, the angular motion of the disk around its axis with the help of the modified Michelson interferometer (see Fig. 2) in which the two arms terminate in two CCR fixed on the disk. The interferometer 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

$$\begin{aligned}\phi(t) &= \phi_0 + \frac{8\pi R}{\lambda}\sin\left(\omega_0 t + \frac{1}{2}\dot\omega t^2\right)\\ &\approx \phi_0 + \frac{8\pi R}{\lambda}\omega_0 t + \frac{4\pi R}{\lambda}\dot\omega t^2\\ &= \phi_0 + 2\pi f t + 2\pi\epsilon t^2,\end{aligned}$$

where λ is the light wavelength, $R = 70$ mm is the distance between the disk axis and each CCR, f is the fringe frequency, and ϵ is the fringe frequency drift. We note that the fringe frequency f is proportional to ω_0, i.e., to the disk angular velocity at $t = 0$ and the frequency drift ϵ is proportional to $\dot{\omega}$, i.e., to the effect to be measured.

In each free fall we collect 43 000 samples of $I(t_n) \equiv I(n\tau) \equiv I_n$. Then we discard the first 7000 samples (140 ms) because of the noise induced in the interferometer by the release systems, and we consider only the subsequent 36 000 samples (0.72 s). For every fringe period, we fit the amplitude A and the offset B. Then we do the best fit of these data with a fourth-order polynomial in t to express the time dependence of the amplitude and the offset as continuous functions, $A(t)$ and $B(t)$. We have checked that a fourth-order polynomial was quite enough to represent the data. The functions $A(t)$ and $B(t)$ are used to unfold the interferometric phase $\phi(n\tau) \equiv \phi_n$. We fit these phase data ϕ_n with the first twenty Chebyshev orthogonal discrete polynomials $Q_k(n)$. We obtain

$$\phi_n = \phi_0 + 2\pi f n\tau + 2\pi\epsilon(n\tau)^2 + \text{noise}$$
$$= \sum_{k=0}^{19} \alpha_k Q_k(n) ,$$

where $0 \leq n \leq N = 36\,000$. It results that

$$\phi_0 = \alpha_0 + \alpha_1 + \alpha_2,$$
$$2\pi f\tau = -\frac{2\alpha_1}{N} + \frac{6\alpha_2}{N-1},$$
$$2\pi\epsilon\tau^2 = \frac{6\alpha_2}{N(N-1)}.$$

Consequently, the value of the Chebyshev coefficient α_2 is a measurement of ϵ, i.e., of the effect we are looking for.

The values of the coefficients $\alpha_3, \ldots, \alpha_{19}$ were used to estimate the random noise affecting the measurement, assuming white noise. This hypothesis was checked by verifying that the α's are Gaussian distributed.

We studied the origin of the noise by sampling both photodiodes PD1 and PD0, during the same free fall. The coefficients $\alpha_1, \ldots, \alpha_{19}$ for the two sets of data were the same, while the difference of the α_0's was correctly equal to π. We have concluded that the interferometric phase noise was indeed the dominant one.

The r.m.s. σ on $\Delta g/g$ coming from this phase noise has been measured to be $\sigma \approx 14 \times 10^{-10}$ per free fall.

The most serious source of systematic error in our measurement is the disk precession. During the free fall, the disk axis precesses around the angular momentum. This motion simulates, in the interferometric phase, the presence of a disk angular acceleration $\dot{\Omega}$ given by

$$\dot{\Omega} = \omega_x \omega_y,$$

where ω_x and ω_y are the disk angular velocity components (at t=0) in the disk plane (ω_x is the component along the vertical). Typical values are $\omega_x, \omega_y \approx 1.5$ mrad/s, simulating disk angular accelerations $\dot{\Omega} \approx 2.2$ μrad/s^2, i.e., a $\Delta g/g \approx 400 \times 10^{-10}$. This systematic effect can be corrected for by measuring ω_x and ω_y. For this reason, we fixed inside each of the two aluminum holders, four plane mirrors (25 mm in diameter and 3 mm in thickness), disposed parallel to the disk plane. In each of the four disk positions, a mirror reflects back, in the horizontal plane, the beam of a He-Ne laser, into a position-sensitive photodiode, oriented along the x-y axis and disposed at $L = 3.3$ m from the disk itself. When the disk starts free falling, we sample every 40 μs the photodiode signals for about 60 ms, before losing the beam. From these signals, we compute the velocity of the beam spot on the photodiode and, therefore, the components ω_x and ω_y.

The uncertainty in the ω_x, ω_y determinations was about 0.15 mrad/s, due to the mirror surface quality. This uncertainty has been evaluated by dividing the data into two parts and by comparing the two consequent determinations of ω_x and ω_y. The error in the ω determination implies, on $\Delta g/g$, an uncertainty $\sigma \approx 60 \times 10^{-10}$ per free fall.

We started our set of measurements using a homogeneous aluminum disk, to check the sensitivity of the apparatus and to look for possible spurious effects. We performed measurements in one disk position and in the conjugate one, obtained by rotating the disk around its axis by 180°. For each free fall we have subtracted from the frequency drift ϵ the contribution due to the disk precession. For each disk position the residuals have been fitted with a Gaussian curve in order to obtain their mean value and their standard deviation. The mean values of the two sets of results were subtracted in order to eliminate possible contributions due to local gravity gradients. With a total of 70 measurements, we obtained the following result:

$$\Delta g/g = (3.2 \pm 9.5) \times 10^{-10}.$$

Then, we started the measurements using copper and aluminum. We used the same experimental procedure as for the homogeneous disk and, with 63 measurements, we obtained

$$\Delta g/g_{\text{Al-Cu}} = (8.5 \pm 9.5) \times 10^{-10}.$$

We reversed the disk and we repeated 65 measurements. We obtained

$$\Delta g/g_{\text{Al-Cu}} = (-4.8 \pm 11.2) \times 10^{-10}.$$

By combining together the two above independent values, we get the present GAL limit on the $\Delta g/g$ for aluminum and copper, which is

$$\Delta g/g_{\text{Al-Cu}} = (2.9 \pm 7.2) \times 10^{-10}. \tag{2}$$

Therefore the sensitivity of the measurement is 7.2 ×

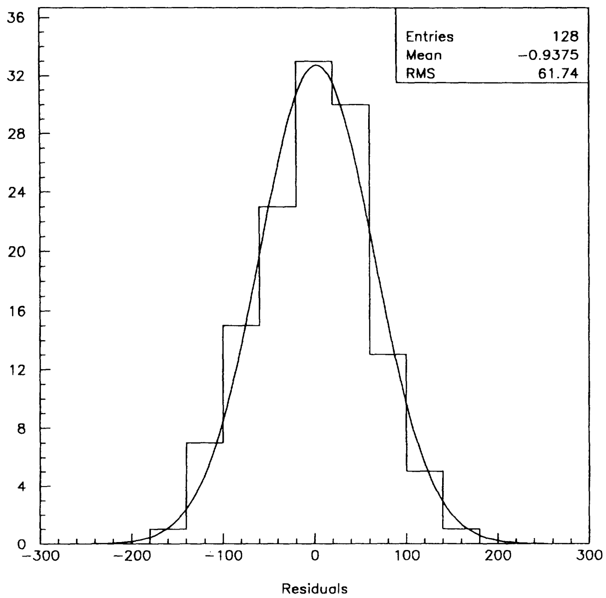

FIG. 3. Histogram of the residuals of the $\Delta g/g$ measurements in units of 10^{-10}, with the best fitting Gaussian curve superimposed on it.

10^{-10}. The distribution of the residuals of the above 128 measurements is shown in Fig. 3.

The result (2) is compatible with zero (no g violation) and it is in quite a good agreement with the one obtained by Kuroda and Mio [9] for the same materials.

According to Eq. (1), the limits on the quantity $\mathcal{K}$ set by the experimental result (2) is

$$|\mathcal{K}| \leq 0.50 \text{ cm}$$

at the 90% confidence level.

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[1] V. Cavasinni, E. Iacopini, E. Polacco, and G. Stefanini, Phys. Lett. A **116**, 157 (1986).
[2] S. Carusotto, V. Cavasinni, E. Iacopini, E. Polacco, and G. Stefanini, in *Fifth Force Neutrino Physics: Proceedings of the XXII Rencontres de Moriond, Les Arcs, January 1988* (Editions Frontières, Gif-sur-Yvette, France, 1988), p. 523.
[3] E. Fischbach, D. Sudarsky, A. Szafer, C. Talmadge, and S. H. Aronson, Phys. Rev. Lett. **56**, 3 (1986).
[4] P. Thieberger, Phys. Rev. Lett. **58**, 1066 (1987).
[5] P. G. Bizzeti, A. M. Bizzeti-Sona, T. Fazzini, A. Perego, and N. Taccetti, Phys. Rev. Lett. **62**, 2901 (1989).
[6] C. W. Stubbs, E. G. Adelberger, F. J. Raab, J. H. Gundlach, B. R. Heckel, K. D. McMurry, H. E. Swanson, and R. Watanabe, Phys. Rev. Lett. **58**, 1070 (1987).
[7] P. E. Boynton, D. Crosby, P. Ekstrom, and A. Szumilo, Phys. Rev. Lett. **59**, 1385 (1987).
[8] T. M. Niebauer, M. P. McHugh, and J. E. Faller, Phys. Rev. Lett. **59**, 609 (1987).
[9] K. Kuroda and N. Mio, Phys. Rev. Lett. **62**, 1941 (1989).
[10] K. Kuroda and N. Mio, Phys. Rev. D **42**, 3903 (1990).
[11] V. L. Fitch, M. V. Isaila, and M. A. Palmer, Phys. Rev. Lett. **60**, 1801 (1988).
[12] D. H. Eckhardt, C. Jekeli, A. R. Lazarewicz, A. J. Romaides, and W. Sands, Phys. Rev. Lett. **60**, 2567 (1988).
[13] C. Jekeli, D. H. Eckhardt, and A. J. Romaides, Phys. Rev. Lett. **64**, 1204 (1990).
[14] E. Fischbach, Nature (London) **356**, 207 (1992).