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Galilean Test for the Fifth Force

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We have carried out a direct free-fall experiment to measure the differential acceleration between two different materials (copper and uranium) falling in the Earth's gravitational field. The differential acceleration was measured to be less than 5 parts in 10^{10} of the normal gravitational acceleration. This null result puts new limits on the strength and range of the proposed fifth force.

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Our experiment is a modern-day counterpart to the experiment Galileo is alleged to have performed from the leaning tower of Pisa. We dropped two objects of differing composition (copper and depleted uranium) in a vacuum, and monitored their motion interferometrically in order to measure any differential acceleration. This experiment was designed to test for a possible fifth force coupled to hypercharge, as proposed by Fischbach *et al.*[1] to explain apparent anomalies in three different types of experiments. The proposed form of the anomalous hypercharge potential between two point masses is

$$U_H = f^2 B_1 B_2 \exp(-r/\lambda)/r, \tag{1}$$

where f and λ are the effective charge and range of the interaction, respectively, and B is the total baryon number. The magnitude of the charge would be about 10^{-19} of the elementary electron charge. The range may be as large as 10^4 m. The effect of this hypothesized fifth force would be to decrease the normal gravitational acceleration of a freely falling body. The anomalous acceleration would depend on the baryon-number–to–mass ratio which depends on the nuclear structure of the substance. Thus, two objects of differing composition would fall toward the Earth at different rates.

The differential acceleration of two bodies toward the Earth is given by the following equation for ranges (λ) smaller than the radius of the Earth (R):

$$\delta a/g \approx \tfrac{3}{2}(\alpha\lambda/R)[B/\mu]_e[B/\mu|_1 - B/\mu|_2][(\rho_s/\rho_m)(1+\zeta)]. \tag{2}$$

The parameter α is the anomaly in G which would arise from the hypothesized fifth force ($G_0 = G_\infty[1+\alpha]$). B/μ is the ratio of the baryon number to the mass given in units of atomic hydrogen. Fischbach *et al.* presented Eq. (2) in their reanalysis of the Eötvös data, except that the density factor shown in brackets was not included. The ratio of the surface density to the mean density ($\rho_s/\rho_m = 1/2$) of the Earth is necessary because of the short range of the hyperphoton. The function ζ expresses the interaction of the hypercharge force with the more dense inner layers of the Earth. ζ can be computed with use of a linear radial density which overestimates the magnitude for ranges less than 2000 km. This model yields

$$\zeta \approx 4\lambda/R. \tag{3}$$

Dropping chambers were used from two of the absolute gravimeters recently developed in our laboratory.[2] These gravimeters measure g by dropping an object in a vacuum. The vertical position of the dropped object is monitored interferometrically and its acceleration is then calculated.

In this Galilean experiment, two dropping chambers are used. They are placed together over a single interferometer base in order to directly measure the differential acceleration of the objects. The apparatus and a block diagram of the optical measurement system is shown in Fig. 1. Two objects of differing composition were allowed to fall freely, each within a drag-free vacu-

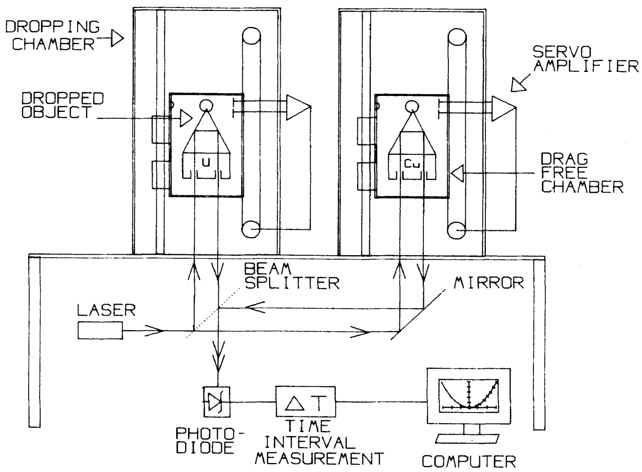

FIG. 1. Schematic diagram of the apparatus used in Joint Institute for Laboratory Astrophysics for the Galilean experiment.

um chamber. The corner cube retroreflector attached to each dropped object formed the end "mirror" of one arm of a Michelson-type optical interferometer. The interferometer produced fringes whose zero crossings were precisely timed (± 100 ps). This information was used to compute the differential acceleration.

Air resistance was overcome using a combination of two different techniques. A vacuum pump reduced the density of air, and a "drag-free chamber" forced the residual air molecules to follow the freely falling object. The objects fell within a drag-free chamber which was servoed to track the object during the descent. The drag-free chamber optically monitored the falling object and maintained a fixed separation (1.5 mm) between itself and the object during the measurement. This chamber isolated the object from air molecules which are not, on average, freely falling. These techniques reduce the vacuum requirement to 10^{-5} Torr. The dropped object and drag-free chamber were both evacuated in a larger stationary container called the dropping chamber, which contained all the components in motion during the measurement. During these experiments, both dropping chambers were evacuated to 10^{-7} Torr.

The two dropping chambers are mounted firmly to a common platform to minimize any differential motions of the chambers. The platform is mechanically separated (except for coupling through the one-foot-thick reinforced concrete floor) from the "interferometer base" which holds the stationary components of the interferometer.

The optical system consists of a frequency-stabilized laser beam which was split and sent vertically to each of the falling objects. The differential radiation pressure on the objects is negligible since the laser power is less than 1 mW. The beams are aligned with the local vertical with a horizontal mercury (or alcohol) reference. The accuracy of the alignment is better than 5″, which is sufficient for an absolute measurement of 0.3 μGal [1 galilei (Gal) $\equiv$ 1 cm/s^2). An error in the verticality of the beams, however, would appear as an anomalous horizontal gradient which was measured by exchanging the location of the dropping chambers. The composition-dependent differential acceleration, obtained after interchanging the chambers, was, therefore, insensitive to the vertical alignment of the beams.

One object was released 25 ms before the other in order to obtain a nearly constant fringe rate of about 800 kHz. These fringes were detected with a 50-MHz-bandwidth avalanche photodiode-amplifier combination. The occurrences of the fringe zero crossings were timed and stored in a computer. The data were then fitted by a parabolic trajectory perturbed with a known vertical gradient (γ). The equation for the differential trajectory is

$$\delta X = \delta X_0 + \delta V_0 t(1+\gamma t^2/6) + \delta g\, t^2/2. \tag{4}$$

The unknowns δX_0, δV_0, and δg are the initial differential displacement, velocity, and acceleration, respectively.

In the absence of a fifth force, the apparatus measures the horizontal and vertical gravity gradients that exist between the two dropped objects. The measured vertical gradient is 2.48 ± 0.1 μGal/cm, while the horizontal gradient between the chambers (east-west) is 2.6 ± 0.8 μGal/cm. These gradients were measured with LaCoste and Romberg relative gravimeters.

These effects can be separated into three independent differential accelerations which are associated with the asymmetries of the experiment (velocity, physical location, and composition). The vertical separation between the objects increases during the drop due to their difference in velocity. Thus, the object with the largest velocity obtains a greater acceleration because of the vertical gradient. The horizontal gradient, however, adds an acceleration because of the physical location of the objects. Finally, there may be a differential acceleration corresponding to the composition of the objects.

The acceleration associated with the velocity is due to the vertical gradient and a correction due to the finite speed of light (SOL). The vertical gradient due to a possible fifth force can be neglected, as it is 2 orders of magnitude smaller than the Earth's normal gravitational gradient. The objects begin their descent at the same height above the floor but one is delayed by 25 ms. This delay introduces a vertical separation of 3 mm at the start of the measurement. The delay also induces a velocity difference between the two objects of 25 cm/s throughout the measurement. These two effects, combined with the vertical gradient, result in a faster acceleration for the object that is dropped first. In addition to the effect of the vertical gradient, there is an apparent differential acceleration due to the finite speed of light. The SOL correction is

$$\delta a_{\mathrm{SOL}} = 3(\delta V/c)g \approx +2.5\ \mu\mathrm{Gal}. \tag{5}$$

The main effect of the vertical gradient was removed by fitting the data by Eq. (4). The residual effect of the gradient (0.7 μGal) due to the initial separation (3 mm) was removed from the final results. The SOL correction was also removed from the final results. These corrections, however, only affect the acceleration of the object that is dropped first. Any composition-dependent acceleration can be extracted by alternating the order in which the objects are dropped. Thus, the result quoted for the experiment is independent of these corrections.

The measured difference in acceleration also includes any horizontal gradient between the two ends of the interferometer. The chambers were separated horizontally (east-west) by 20.3 cm, which resulted in an estimated differential acceleration of 0.5 μGal. This acceleration is tied to the spatial location of the object and can be distinguished from a composition-dependent acceleration by exchanging the positions of the two dropped objects.

We used four different experimental configurations in order to differentiate between the three classes of accelerations. First, two different measurements were taken where the leading object was alternated between copper and uranium. The physical locations of the chambers were then interchanged and the starting time delay was again alternated between the two objects. These four measurements form a highly symmetric set of experimental conditions from which any differential acceleration corresponding to a fifth force can be extracted.

The uncertainty on each drop was generally less than 50 μGal and the measurement was repeated every 15 s. Fifty sets, each consisting of 375 drops, were taken during the course of this experiment. The experimental conditions for each set were chosen by cycling through the four configurations. The three differential accelerations associated with the initial velocity, horizontal gradient, and fifth force were estimated with use of a linear least-squares analysis of the data. The results of this procedure and the associated 1σ uncertainties can be seen in the following.

Asymmetry	Differential acceleration (μGal)
Initial velocity	-0.17 ± 0.50
Horizontal location	$+0.10 \pm 0.69$
Composition	$+0.13 \pm 0.50$

Only the last differential acceleration is directly relevant to the determination of the fifth force. The first two values merely reflect corrections to the measured horizontal and vertical gradients. However, the agreement of these results with zero is encouraging, as they are an indirect measurement of possible systematics.

The value associated with the initial velocity is the differential acceleration between the leading object and the slower object. The value shown above contains a correction due to the speed of light (2.5 μGal), and the effect of the vertical gradient over the initial separation (0.7 μGal). The value is well within the uncertainty, indicating that this measurement agrees with the vertical gradient (2.48 μGal/cm) previously obtained with relative gravimeters.

The term due to the horizontal gradient is the difference in the acceleration between the object located on the eastern arm of the interferometer and that at the western location. The value includes the estimated horizontal gradient (0.5 μGal) between the chambers. The uncertainty on this measurement is larger than the statistical estimate obtained with the least-squares analysis. The larger uncertainty reflects possible errors in the alignment of the interferometer arms with the local vertical.

Finally, the value associated with the fifth force (the third entry in the table) is the differential acceleration of the object containing a copper weight and the object with a uranium weight. Our data are consistent with zero acceleration difference between the two objects. Therefore, this result indicates that the proposed hypercharge interaction is less than our experimental sensitivity. This null result places a constraint on any possible baryon-dependent force.

The baryon-number-to-mass ratio is obtained by averaging over all the materials in each object. Both objects contain 102.5 g of structural materials with an average baryon-number-to-mass ratio nearly equal to that of aluminum. This weight is dominated by a glass cornercube (the retroreflector) and its associated aluminum fixtures.

A 40.0-g copper weight was attached to one object, while the other carried two disks (199.25 g together) of machine depleted uranium. These counterweights locate the optical center of the cornercubes at the center of mass of the objects, as well as providing a fifth-force signal. The difference in baryon-number-to-mass ratio of the two dropped objects was

$$\delta(B/\mu) = 7.1 \times 10^{-4}. \tag{6}$$

This difference is about half what one would expect if pure copper and uranium were used as the dropped objects. More recent proposals have been made for a fifth-force coupling to lepton number.[3] Our result is about 80 times more sensitive for interactions coupling to lepton number. More specifically, the difference in lepton-number-to-mass ratio of the two objects was

$$\delta(L/\mu) = 5.6 \times 10^{-2}. \tag{7}$$

Equation (1) can be combined with the measured differential acceleration and baryon-number-to-mass ratio of the two objects in order to constrain the product $\alpha\lambda$. This experiment gives the following bound {where we have neglected the second-order term resulting from the Earth's radial density variation [Eq. (3)]}:

$$\alpha\lambda = 1.6 \pm 6.0 \text{ m}, \tag{8}$$

which is clearly inconsistent with the value obtained in

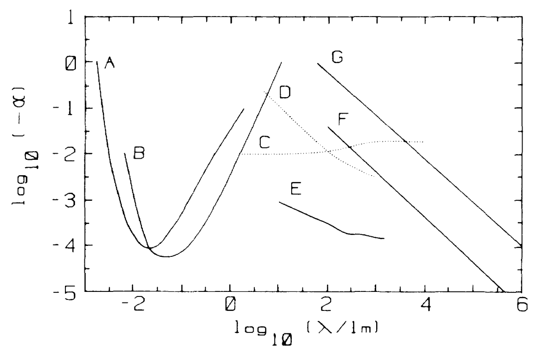

FIG. 2. Curves A through E correspond to data and analysis in Refs. 7–11; F represents the Galilean result [Eq. (8)] plotted at the level of 1 standard deviation. Inclusion of ζ [Eq. (3)] does not substantially affect the curve over the ranges shown. G was obtained with satellite data (see Refs. 12 and 13). Dashed lines represent positive results and the solid lines represent null results.

the reanalysis of the Eötvös experiment ($\alpha\lambda = 24 \pm 3$ m) done by Fischbach *et al.*[1] However, as pointed out by Eckhardt[4] and others, a short-range force has no effect on the Eötvös results except through local mass inhomogeneities. Fischbach *et al.*[5] acknowledge that the value of α cannot be derived without this information.

The precision of our experiment at 200 m is not competitive with the geophysical limit[6] as interpreted by Fischbach *et al.*[1] However, our result indicates that the anomaly in the geophysical data is not due to the proposed fifth force at ranges larger than 1 km.

The results obtained by several contemporary experiments are shown in Fig. 2. The solid lines represent experiments with a null outcome and exclude values of α and λ which lie above the curves. The dashed lines represent experiments that are consistent with an anomalous force having a value of α and λ lying somewhere on their respective curves. The limits on the fifth force set by all the null experiments are in disagreement with both positive results shown in Fig. 2, except in the narrow region of 1–10 m.

Torsion balances place the best limits on short to medium ranges (0.01–1000 m). These rely on masses which are located horizontally relative to the apparatus. The medium-range results are also sensitive to variations of the horizontal density of the Earth. Thus, the interpretation of the data requires an integration over the nearby topography, with use of some model for the density. Anomalous mass distributions on the Earth are not always well characterized by topography alone and, in general, gravity data must also be utilized. This complicates the interpretation of hillside experiments at longer ranges. The authors of the most recent torsion experiment (recognizing this) quote their results only to 1.4 km.[9]

Our value, however, is sensitive to the mass directly below the apparatus, and is not affected by horizontal mass anomalies. Furthermore, isostatic compensation of horizontal mass only improves the validity of this interpretation. Thus, the limit given by this experiment can be extended to longer ranges (0.1–1000 km).

The result of our experiment, because of the differential design, is independent of gravitational noise due to tides, air pressure, or water-table variations. These noise sources would normally make sub-μGal precision impossible.

This experiment extends the α-λ region over which the usual gravitational laws are valid. Our Galilean limit, on a possible fifth force coupled to hypercharge, provides approximately an order-of-magnitude improvement over that previously obtained with use of satellite data (Fig. 2).

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