Test of a Composition-Dependent Force by a Free-Fall Interferometer

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We have obtained an experimental null result for a possible composition-dependent force by a newly developed Galilean method in which we measured the acceleration difference between two objects freely falling simultaneously in a vacuum chamber. The data on two pairs of objects, an aluminum-copper pair and an aluminum-carbon pair, indicate $|\xi|\lambda < 9$ m if baryon coupling and a simple model of the Earth is assumed.

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The search for a possible fifth force, suggested by reanalysis of the classical Eötvös experiment,[1] has resulted in several conflicting measurements.[2-9] While theoretical efforts, adopting sources other than the baryon number, have been made to reconcile these incompatible results, no one has yet succeeded in explaining the discrepancies. Under the circumstances, we cannot with confidence state that the force which couples to the baryon number has been completely tested by experiment. More precise and reliable experiments are necessary to test the first suggestion offered by Fischbach *et al.*[1] We therefore conducted a free-fall experiment using an optical Michelson interferometer and a newly developed cocentered system to measure the acceleration difference between two freely falling objects. Although the principle is the same as the experiment of Niebauer, McHugh, and Faller,[5] our design features can reduce systematic errors which have been pointed out in their paper, as shown later. We obtained a null result with a sensitivity of less than a few μGal (1 Gal$=0.01$ m/s^2) between two pairs of objects, an aluminum-copper (Al-Cu) and an aluminum-carbon (Al-C) pair. This accuracy is slightly lower than that obtained by Niebauer, McHugh, and Faller with an uranium-copper pair.[5]

If there is a force coupling to the baryon number with strength ξ and force range λ, the potential Φ including gravity between two point masses m_i and m_j is written as

$$\Phi = -G_\infty m_i m_j [1-(B_i B_j/\mu_i \mu_j)\xi \exp(-r/\lambda)]/r\,, \quad (1)$$

where G_∞ is the gravitational constant at a very large distance, B_i and B_j are the baryon numbers of i and j, and μ_i and μ_j are the corresponding masses in units of atomic hydrogen. The first term of Eq. (1) represents Newtonian gravity and the second, the possible fifth force. According to this baryon-coupling force, two objects of different compositions fall with different accelerations indicating an apparent break of the equivalence principle. On the Earth, which is assumed to be a sphere of radius R with uniform density ρ, the acceleration difference between two objects is approximated by[10]

$$\Delta a_{jk} \sim \tfrac{3}{2} g(\xi\lambda/R)\Delta(B/\mu)_{jk}\,, \quad (2)$$

assuming $\lambda \ll R$ and $|\xi| \ll 1$, where g is $4\pi G_\infty \rho R/3$ and $\Delta(B/\mu)_{jk}$ denotes the difference between the two objects. Notice that we took a simple model of the Earth with uniform density for the first approximation, in accordance with the reanalysis of the Eötvös experiment.[1] If the density variation of the Earth is taken into consideration, Eq. (2) should be modified as shown in Ref. 5. In the reanalysis of the Eötvös experiment,[1] $|\xi|\lambda$ was estimated to be 24 m. This interpretation of the reanalysis is considered to be invalid in the force range less than $\lambda \sim 1$ km because of local horizontal mass inhomogeneities.[11] Moreover, many experiments put a much more stringent limit on $|\xi|\lambda$ in this range. Nevertheless, if λ is larger than a few kilometers, there are only a few experiments sensitive to such a "long-range" force and the limits obtained are not far from the above value. In accordance with this magnitude of the force and Eq. (2), the acceleration difference would amount to 3.6 μGal for the Al-C pair in our experiment.

Our free-fall interferometer is shown schematically in Fig. 1. Here, a pair of objects is released in a vacuum chamber [$(2\text{–}3)\times10^{-7}$ Torr] and the acceleration difference is measured by a Michelson-type laser interferometer. The main part of the interferometer is mounted on the two objects. The upper object B has both a cube beam splitter (BS) S, and a corner cube prism (CCP) C_B; whereas the lower object A has only a corner cube prism C_A. The CCP's are 15 mm in diameter. Light from a stabilized He-Ne laser (0.633 μm) is introduced into the interferometer from the upper side of the chamber through a beam expander ($\times 10$) and an aperture (5 mm in diameter). The interfering light from the interferometer has a beam frequency $\Delta\nu$ in accordance with the velocity difference ΔV between the optical centers of the CCP's in A and B due to the Doppler effect, as follows:

$$\Delta\nu = 2(\Delta V)\nu/c\,, \quad (3)$$

where ν is the frequency of the laser light and c is the velocity of light. If there is no acceleration difference between the two objects, $\Delta\nu$ remains constant during the fall. This interferometer system has the merit of eliminating the so-called Abbe's error[12] which occurs when

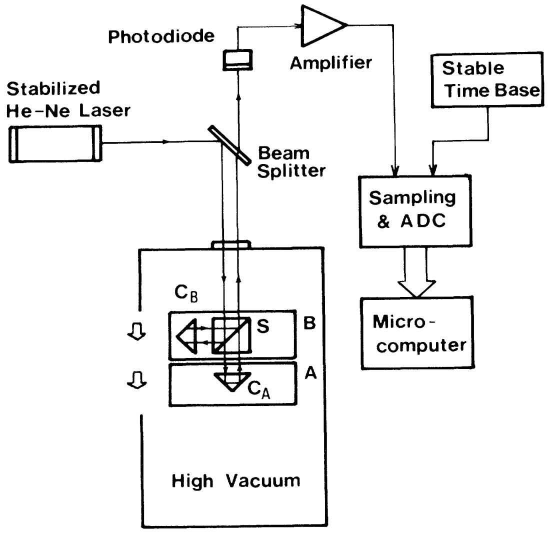

FIG. 1. A schematic block diagram of the free-fall interferometer. A pair of objects is released in a vacuum chamber and the acceleration difference is measured by a Michelson-type laser interferometer during the fall. This optical system can eliminate the so-called Abbe's error caused by laser-beam tilting.

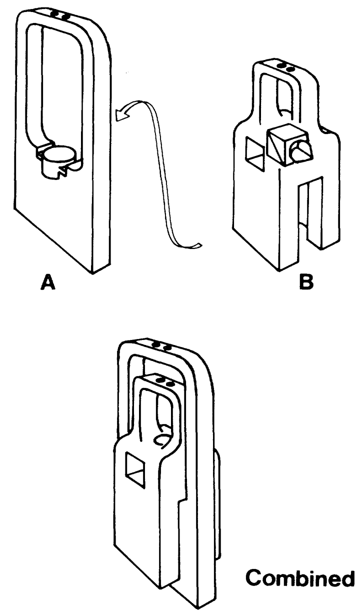

FIG. 2. Falling objects. The mass centers of the two objects are designed to coincide with each other to avoid the gravity-gradient effect. The lower object A, 139 mm in height, is replaced by another one made of a different material. The upper object B, 114 mm in height, is made of aluminum. In the upper portion of each object, there are two holes for laser beams, and attached to the underside, at the midpoint between these holes, there is a pivot bearing for support.

the laser source tilts as a results of seismic noises or accidental deformation of the frames. The pair of objects falls from a height of about 60 cm. The electrical signal, derived from a p-i-n photodiode during the 0.35-s fall, is sampled every 4 μs, timed by a precise crystal oscillator and stored in a computer memory.

The pair of objects was intuitively designed, as shown in Fig. 2, to facilitate silent release and to avoid the effect of the gravity gradient by having the centers of mass coincide. The center of mass of object A was set at the optical center of the CCP mounted on A, whereas the center of mass of object B was set at the reflected image point of the optical center of the CCP buried in object B. Each object had two symmetrical holes for laser beams in its upper portion as well as a single pivot bearing attached to the underside at the midpoint between the holes. Before the fall, the pair of objects was combined in the manner illustrated in Fig. 2, with each pivot bearing mounted on a small stainless-steel ball of the release mechanism[13] which functioned in two stages as depicted in Fig. 3. The error in placing the mass center of A on the mass center of B was within 0.3 mm. Except in coupling to higher-mass multipole moments, the gravity gradient was estimated to produce a 0.1-μGal difference, which was negligible. We fashioned two single-plate objects of different materials (copper and carbon) for object A. The height of object A was 139 mm. The copper object was 119 g in total weight (copper, 116 g; glass, 3 g), and the carbon object was 120 g in total weight (carbon, 113 g; aluminum, 4 g, glass, 3 g). Object B was made of aluminum and was 160 g in total weight (aluminum, 149 g; glass, 11 g) and 114 mm in height. Through this system of falling objects and the release mechanism, we were able to realize a silent drop with an angular velocity as small as $\sim 10^{-3}$ rad/s for each falling object.

When one object rotates with the uniform angular ve-

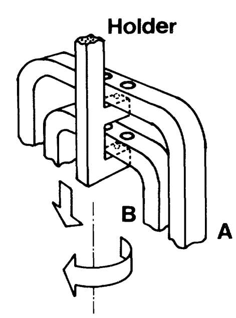

FIG. 3. Falling objects on the release mechanism. Each object is hung at the pivot bearing on a small stainless-steel ball attached to the holder of a release mechanism. The error in placing the mass center of A on B is within 0.3 mm. The release is done in two steps: First, the holder drops faster than in a free fall by 50 μm. Next, the holder slides down by 5 mm and escapes from the trajectory of the falling objects by rotation.

locity $\dot{\phi}$ during its fall, the second-order change of the optical length in the CCP produces a false acceleration difference Δa_F, given by

$$\Delta a_F = 2n\epsilon\dot{\phi}^2 , \qquad (4)$$

where ϵ is the vertical separation of the optical center from the center of mass and n is the refractive index of the CCP.[14,15] This effect occurs in both objects, which rotate with different angular velocities during the fall. Notice that a path change in BS due to angular rotation enters equally into both light paths and is canceled. Since ϵ is smaller than 0.2 mm, the false acceleration difference due to CCP tilting is estimated to be smaller than 0.3 μGal on the average.

Other systematic error sources which have clearly been identified thus far are residual gas, absorbed gas, mutual gravitational pull, and electrostatic force. Residual gas produces a repulsive force between the pair, and the magnitude is estimated to be less than 0.3 μGal, as obtained by extrapolating data collected at two vacuum pressure points: 1×10^{-6} and 1×10^{-5} Torr. Because of the lack of a return mechanism which resets the pairs in the chamber, we had to open the vacuum chamber for every fall. For this reason, we cannot disregard the effect of absorbed gas released from the surfaces of the objects in vacuum. The released gas also produced a repulsive force, and the effect heavily depended on the evacuation time. We experimentally decided on an evacuation time of more than 8 h. Mutual gravitational pulls between the objects were numerically calculated by the Gauss-Legendre method. The acceleration differences due to the effect were 0.28 μGal for the Al-Cu pair and 0.31 μGal for the Al-C pair. These values were used to correct the data. Electrical charges on the objects interacted with each other and became a source of error. By electrical grounding before the fall, the amount of the charge during the fall was reduced to less than 1 pC. Since a charge of 1 pC on each object at opposite signs is estimated to produce an acceleration difference of less than 0.01 μGal, the electrostatic force was negligible. In the case of equal signs, the electrostatic force was repulsive, and this augmented the acceleration difference due to the residual gas and the absorbed gas released. Therefore, there was no possibility of canceling out these errors. The contribution of these systematic errors to the acceleration difference was far less than 1 μGal.

The corrected acceleration differences obtained thus far are -0.13 ± 0.78 μGal for the Al-Cu pair and -0.18 ± 1.38 μGal for the Al-C pair (Table I), where each error indicates 1 standard deviation of the averaged data from the repetition number, assuming a normal distribution. We could not detect the expected anomaly within the experimental errors. The main source of the statistical errors was related to unexpected movements of the release mechanism at the instant of release due to microseismic and/or manmade noises. The movements' effect on the acceleration difference may be attributed to laser-beam walks relative to the optical pieces during the fall.[16] Figure 4 shows our null result plotted with the data for the original figure presented in Ref. 1. This figure shows a direct comparison of our result with the reanalysis of the classical Eötvös experiment, if the force range is large and the difference of local mass distribution between the site of the classical experiment and our basement can be neglected. If baryon coupling is assumed, our null result sets $|\xi|\lambda < 9$ m. According to Niebauear, McHugh, and Faller, this limit should be doubled in the range less than $\lambda\sim10^3$ km.[5] In the range less than $\lambda\sim1$ km, this limitation is lower than any other null results published thus far. Nonetheless, this sets a reliable limit with Niebauear, McHugh, and Faller in the range of more than $\lambda\sim10$ km.

We conclude that the magnitude given in Ref. 1 cannot be reproduced by our free-fall method. Our aim of testing the baryon-coupling force at the 1-μGal level for multiple pairs of objects was successfully achieved

TABLE I. List of null data obtained by the free-fall interferometer for two pairs of objects, an Al-Cu pair and an Al-C pair. The difference B/μ between the objects was calculated taking all object compositions into consideration. Errors are statistical only.

Combination	Acceleration difference (μGal)	Repetition number	$10^3\Delta(B/u)$
Al-Cu	-0.13 ± 0.78	8	-0.42
Al-C	-0.18 ± 1.38	20	0.65

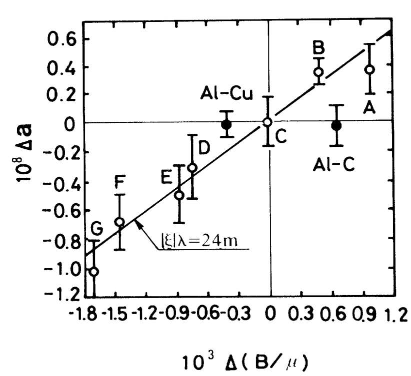

FIG. 4. Result of the experiment. Filled circles represent our null result, plotted with the data for the original figure presented in Ref. 1. The ordinates are 10^8 times the acceleration differences and the abscissas are 10^3 times the differences of B/μ. The straight line denotes $\xi\lambda=24$ m, which is rejected by many experiments including ours. Symbols are *A*, Cu-Pt; *B*, magnalium-Pt; *C*, Ag-$FeSO_4$; *D*, asbestos-Cu; *E*, $CuSO_4\cdot5H_2O$-Cu; *F*, $CuSO_4$(solution)-Cu; and *G*, H_2O-Cu.

through use of the free-fall interferometer. Our method has potential for more accurate measurement of the acceleration difference, although some improvement of the apparatus is required.

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[1]E. Fischbach, D. Sudarsky, A. Szafer, C. Talmadge, and S. H. Aronson, Phys. Rev. Lett. **56**, 3 (1986).

[2]P. Thierberger, Phys. Rev. Lett. **58**, 1066 (1987).

[3]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).

[4]P. E. Boynton, D. Crosby, P. Ekstrom, and A. Szumilo, Phys. Rev. Lett. **59**, 1385 (1987).

[5]T. M. Niebauer, M. P. McHugh, and J. E. Faller, Phys. Rev. Lett. **59**, 609 (1987).

[6]V. L. Fitch, M. V. Isaila, and M. A. Palmer, Phys. Rev. Lett. **60**, 1801 (1988).

[7]D. H. Eckhardt, C. Jekeli, A. R. Lazarewicz, A. J. Romaides, and W. Sands, Phys. Rev. Lett. **60**, 2567 (1988).

[8]C. C. Speake and T. J. Quinn, Phys. Rev. Lett. **61**, 1340 (1988).

[9]R. Cowsik, N. Krishnan, S. N. Tandon, and C. S. Unnikrishnan, Phys. Rev. Lett. **61**, 2179 (1988).

[10]K. Kuroda and N. Mio, in *Fifth Force and Neutrino Physics,* edited by O. Fackler and J. Tran Thanh Van, Proceedings of the Seventh Moriond Workshop, Les Arcs, France, 1988 (Editions Frontieres, Gif-sur-Yvette, 1988), p. 515.

[11]E. Fischbach, D. Sudarsky, A. Szafer, C. Talmadge, and S. H. Aronson, Phys. Rev. Lett. **56**, 2424 (1986).

[12]When you measure temperature by means of a thermometer, for example, the Abbe's error $L \sin\theta$ emerges, where L is the length between the spirit and the measure, and θ is the angle which the line running from your eye to the spirit edge forms with the horizontal line.

[13]K. Kuroda and N. Mio, in Proceedings of the 1988 IEEE Conference on Precision Electromagnetic Measurements (to be published).

[14]Edson R. Peck, J. Opt. Soc. Am. **38**, 1015 (1948).

[15]J. A. Hammond and J. E. Faller, in *Precision Measurement and Fundamental Constants,* NBS Special Publication No. 343 (U.S. GPO, Washington, DC, 1970), p. 457.

[16]At the instant of release, the upper object may have a small initial horizontal velocity in the eastern direction, for example, while the lower one has a velocity in the western direction. During the fall, the light beam, which traces the surfaces of the optical pieces, which are not strictly flat but slightly rounded, produces an extra phase shift, resulting in an error in the acceleration difference.