Test of the Equivalence Principle for Ordinary Matter Falling toward Dark Matter

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We tested the equivalence principle (EP) for Be, Cu, and Al falling toward the galactic center, and found $\Delta a(\mathrm{Be,Cu}) = (-0.1 \pm 5.8) \times 10^{-12}$ cm/s^2 and $\Delta a(\mathrm{Be,Al}) = (3.6 \pm 6.9) \times 10^{-12}$ cm/s^2. As dark matter is thought to account for (25–30)% of our galacticentric acceleration, the EP parameters for Be/Cu, or Be/Al, falling toward dark matter, are $\eta(\mathrm{Be,Cu}) = (0.0 \pm 1.2) \times 10^{-3}$ and $\eta(\mathrm{Be,Al}) = (0.7 \pm 1.4) \times 10^{-3}$ (1σ errors). This limits any EP-violating component of our acceleration toward dark matter and provides laboratory evidence that gravitation is the only significant long-range interaction between dark and ordinary matter.

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Studies of the tangential velocities of luminous matter in galaxies have shown that the observed centripetal accelerations are much greater than can be accounted for by the gravitational attraction of other luminous matter [1, 2]. These and other studies are taken to indicate that the majority of mass in a galaxy is nonluminous dark matter. A large number of candidates for this dark matter have been proposed, ranging from the ordinary (normal baryonic matter in the form of large, dark planets) to the exotic [3] (axions, weakly interacting massive particles, massive neutrinos, massive black holes, etc.). Because very little is known about the nature of the dark matter except that it accelerates ordinary matter and deflects photons, it is interesting to ask if laboratory experiments can probe the long-range fields generated by the dark matter and provide a direct test of the usual assumption that gravitation is the only significant long-range interaction between dark matter and ordinary matter.

The equality of the accelerations of two different bodies falling toward a third body (the equivalence principle) has been tested with great precision [4–6] and establishes that gravitation is the only perceptible long-range interaction acting between electrically neutral bodies of *ordinary* matter. Upper limits on possible nongravitational interactions between *dark matter* and *dark matter* have recently been inferred from astrophysical and cosmological considerations [7]. In this paper, we follow the ideas of Stubbs presented in the preceding Letter [8], and report an experimental test of the equivalence principle (EP) for *ordinary matter* falling toward *dark matter.*

Our results were obtained by analyzing new data [9] from the Eöt-Wash torsion balance taken over a 24 month period from August 1990 to July 1992 [10]. This balance [6], normally used to test the EP for objects in the gravitational field of the Earth, was recently upgraded [9] to achieve performance within a factor of 3 of the thermal limit. The instrument consists of a torsion pendulum containing two Be and two Cu (or two Be and two Al) test bodies arranged as a composition dipole. The entire balance rotates continuously around a vertical axis with a period τ that is an integer multiple N of the free torsional-oscillation period of the pendulum. The Be/Cu data were taken with $N = 8$, $\tau = 1.54$ h; the Be/Al data with $N = 9$, $\tau = 1.73$ h.

The angular deflection θ of the torsion pendulum relative to the rotating optical read-out system was measured as a function of the pendulum orientation in the laboratory frame ϕ. A composition-dependent acceleration of the test bodies would produce a sinusoidal modulation of θ. The values of θ, ϕ, and 17 other sensors (temperatures, tilts, etc.) were recorded every 19.3 s, and the EP-violating signal was extracted by Fourier analysis of $\theta(\phi)$. A linear drift in θ due to slow relaxation of the suspension fiber was suppressed by the digital filter transformation $\tilde{\theta}(\phi) = [\theta(\phi) - \theta(\phi + \pi)]/2$. The filtered data were then averaged over successive torsional cycles and the results fitted by the expression

$$\theta(\phi) = b_0 + \sum_{n=1}^{3} (a_n^{\cos} \cos n\phi - a_n^{\sin} \sin n\phi) , \quad (1)$$

where b_0 is constant and the sum over n runs up to 3 to account for the effects of gravity gradients on the pendulum [11].

The $a_1^{\sin}$ and $a_1^{\cos}$ coefficients contain the EP-violating signal and would be constants were the Earth the source of the EP-violating force. The $a_1^{\sin}$ and $a_1^{\cos}$ coefficients also receive contributions from systematic effects (primarily turntable imperfections) that are fixed in the laboratory frame. Such systematic effects are normally subtracted by combining data taken with various orientations of the composition dipole on the pendulum tray (see Ref. [6]). A celestial EP-violating source would cause the $a_1^{\sin}$ and $a_{\cos}^{1}$ coefficients to vary with a period of a sidereal (or solar) day. We searched for an EP-violating signal associated with the direction toward the galactic center and eliminated spurious effects fixed in the laboratory frame by dividing the data for each test body pair into segments containing precisely two complete rotations of the apparatus, and extracted the $a_1^{\sin}$ and $a_1^{\cos}$ coefficients associated with each segment. Next we computed the altitude ϑ and azimuth φ of the galactic center at the effective midpoint of each data segment. As the galactic center moved by only 46° (51°) during one segment of Be/Cu (Be/Al) data, we could approximate the Galaxy as a source that remained stationary during a segment. Our results are corrected for the small attenuation of the EP-violating signal due to this approximation ($\approx$ 6% and $\approx$ 7% for Be/Cu and Be/Al, respectively). A set of $a_1^{\sin}$ and $a_1^{\cos}$ coefficients from several weeks of continuous data accumulation was then fitted by

$$a^{\sin} = k\cos\vartheta[-\cos(\varphi-\phi_0)\Delta a - \sin(\varphi-\phi_0)\Delta a^*] + c^{\sin}\ ,$$
$$a^{\cos} = k\cos\vartheta[+\sin(\varphi-\phi_0)\Delta a - \cos(\varphi-\phi_0)\Delta a^*] + c^{\cos}\ , \tag{2}$$

where $k = 8.43\times10^{-4}$ cm/s^2 rad is a property of our instrument, Δa is the differential acceleration toward the galactic center [12], Δa^* is a quadrature acceleration that is expected to vanish within the errors of the measurement, and ϕ_0 specifies the orientation of the composition dipole when $\phi = 0$. The constants $c^{\sin}$ and $c^{\cos}$ account for effects fixed in the laboratory frame.

This analysis was carried out for each set of experimental conditions (test-body materials, orientation of the composition dipole on the pendulum tray, etc.); the uncertainties in the resulting Δa and Δa^* values were inferred from the scatter of the individual segment points. Figure 1 shows the results from one of these data sets. Combining 18 such Be/Cu data sets involving 6 changes of the dipole orientation on the pendulum tray, we obtained the 1σ result

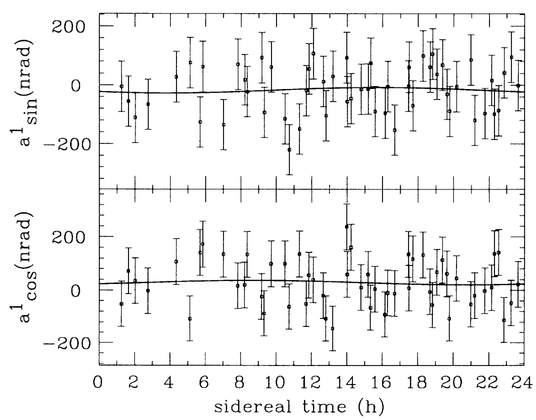

FIG. 1. One set of rotating balance data used to extract the differential acceleration of Be and Cu toward the galactic center. The observed $a_1^{\sin}$ and $a_1^{\cos}$ amplitudes of two-cycle data segments (100 nrad corresponds to $\Delta a = 8.43\times10^{-11}$ cm/s^2) are plotted vs sidereal time (modulo one sidereal day). These data were fitted with four free parameters: two constant instrumental offsets that accounted for torques fixed in the laboratory frame, plus torques proportional to the horizontal component of Δa and its quadrature. This plot shows 54 segments taken under identical experimental conditions, and the best fit which yielded $\Delta a = 1\pm17$ nrad and $\Delta a^* = 13\pm17$ nrad. A total of 522 Be/Cu and 494 Be/Al segments were used in our analysis.

$$\begin{aligned}\Delta a(\mathrm{Be,Cu}) &= (-0.1\pm5.8)\times10^{-12}\ \mathrm{cm/s^2}\ ,\\ \Delta a^*(\mathrm{Be,Cu}) &= (+0.4\pm5.8)\times10^{-12}\ \mathrm{cm/s^2}\ ,\\ \chi^2/\nu &= 0.8\ ,\end{aligned} \tag{3}$$

while from 17 Be/Al data sets involving 7 changes of the dipole orientation, we obtained the 1σ result

$$\begin{aligned}\Delta a(\mathrm{Be,Al}) &= (+3.6\pm6.9)\times10^{-12}\ \mathrm{cm/s^2}\\ \Delta a^*(\mathrm{Be,Al}) &= (-3.7\pm6.9)\times10^{-12}\ \mathrm{cm/s^2}\\ \chi^2/\nu &= 0.8\ ,\end{aligned} \tag{4}$$

which are consistent with a null effect. The entire analysis procedure was verified with a Monte Carlo program that generated artificial data containing a known galactic signal along with a noisy laboratory-fixed signal.

By comparing the measured Δa's to the known [2] centripetal acceleration of the solar system toward the galactic center

$$a_{\mathrm{gal}} = \omega^2 r_\odot = 1.85\times10^{-8}\ \mathrm{cm/s^2}\ , \tag{5}$$

where $\omega = (8.4\pm1)\times10^{-16}$ s^{-1} is the rotation frequency of our galaxy and $r_\odot = 8.5\pm1$ kpc is the distance of the Sun from the galactic center, we obtain constraints on the EP-violating parameter η for objects falling toward the center of our galaxy

$$\begin{aligned}\eta(\mathrm{Be,Cu}) &= \Delta a(\mathrm{Be,Cu})/a_{\mathrm{gal}}\\ &= (-0.1\pm3.1)\times10^{-4}\ ,\\ \eta(\mathrm{Be,Al}) &= \Delta a(\mathrm{Be,Al})/a_{\mathrm{gal}}\\ &= (+1.9\pm3.7)\times10^{-4}\ .\end{aligned} \tag{6}$$

As there is ample evidence that the EP is satisfied to high precision by ordinary matter falling toward ordinary matter (our own results [6] indicate that for Be and Cu falling in the Earth's field $|\eta| \le 1.2\times10^{-11}$) we can use our galactic results to probe the EP for ordinary matter falling toward the dark matter in the galaxy. Although the rotation-curve data indicate that dark matter constitutes about 90% of the total galactic mass, the dark matter is believed to be distributed in a large-diameter halo that extends well past $r_\odot$. Therefore, as discussed by Stubbs in the preceding Letter [8], one expects $a_{\mathrm{gal}}^{\mathrm{DM}}$, the acceleration towards the galactic center due to the dark matter in our galaxy, to be (25–30)% of a_{gal}. We assume

$$a_{\mathrm{gal}}^{\mathrm{DM}} \approx 5\times10^{-9}\ \mathrm{cm/s^2}\ , \tag{7}$$

and obtain the EP tests for Be, Cu, and Al falling toward dark matter:

$$\begin{aligned}\eta^{\mathrm{DM}}(\mathrm{Be,Cu}) &= \Delta a(\mathrm{Be,Cu})/a_{\mathrm{gal}}^{\mathrm{DM}}\\ &= (0.0\pm1.2)\times10^{-3},\\ \eta^{\mathrm{DM}}(\mathrm{Be,Al}) &= \Delta a(\mathrm{Be,Al})/a_{\mathrm{gal}}^{\mathrm{DM}}\\ &= (+0.7\pm1.4)\times10^{-3}\ ,\end{aligned} \tag{8}$$

where the uncertainty in $a_{\rm gal}^{\rm DM}$ is not included because we do not know how to evaluate it.

If we separate the acceleration of ordinary matter due to dark matter into its gravitational and nongravitational (i.e., EP-violating) components, $a_{\rm gal}^{\rm DM} = a_g^{\rm DM} + a_{ng}^{\rm DM}$, then the result in Eq. (9) probes the *differential* contribution of $a_{ng}^{\rm DM}$ for two materials (Be and Al, or Be and Cu). What can this result tell us about the *total* nongravitational acceleration of ordinary matter due to dark matter? The nongravitational potential of an infinite-ranged vector or scalar interaction that couples to a charge q_5 can be expressed as

$$V_{ng}(r_{12}) = \frac{g_5^2}{4\pi G}\left(\frac{q_5}{m}\right)_1\left(\frac{q_5}{m}\right)_2 V_g(r_{12}) \ , \qquad (9)$$

where g_5 is the coupling constant of the EP-violating interaction, q_5/m is the q_5-to-mass ratio of a body, and V_g is the usual gravitational potential. Hence

$$\frac{a_{ng}^{\rm DM}}{a_{\rm gal}^{\rm DM}} = \eta^{\rm DM}\frac{\langle q_5/m\rangle}{\Delta(q_5/m)} \ , \qquad (10)$$

where $\langle q_5/m\rangle$ is the average of the two test-body q_5-to-mass ratios and $\Delta(q_5/m)$ is their difference. (Note that this relation is independent of the q_5-to-mass ratio of dark matter.) Equation (10), when combined with the values in Eq. (9) is our *basic experimental constraint.* To proceed further, one must evaluate the quantity

$$R = \frac{\langle q_5/m\rangle}{\Delta(q_5/m)} \qquad (11)$$

for our two detector test-body pairs.

An EP-violating interaction could arise from the exchange of scalar or vector bosons. However, a significant *vector* interaction between dark and ordinary matter is already excluded by conventional Eötvös experiments plus the requirement that the dark matter halos be stable against the repulsive vector dark-matter–dark-matter interaction. Halo stability requires

$$\frac{g_5^2}{4\pi G}\left(\frac{q_5}{m}\right)^2_{\rm DM} < 1 \ , \qquad (12)$$

while conventional Eötvös experiments [4–6] establish that, roughly speaking,

$$|\eta^{\rm OM}| = \frac{|\Delta a|}{a} = \frac{g_5^2}{4\pi G}\Delta\left(\frac{q_5}{m}\right)_{\rm det}\left(\frac{q_5}{m}\right)_{\rm OM} < 10^{-12} \ , \qquad (13)$$

where the subscript det refers to the torsion-balance detector, and OM to the ordinary matter that is the "source" for these experiments. Equations (12) and (13) can be combined to constrain the total vector acceleration of ordinary matter toward dark matter

$$\frac{a_{ng}^{\rm DM}}{a_g^{\rm DM}} = \frac{g_5^2}{4\pi G}\left(\frac{q_5}{m}\right)_{\rm OM}\left(\frac{q_5}{m}\right)_{\rm DM} < \sqrt{\eta^{\rm OM}}R \ , \qquad (14)$$

where for vector interactions R, which is easily calculated once the charge is specified, has a characteristic value of order 10^3.

Scalar interactions (which would produce an attractive dark-matter–dark-matter force) are not ruled out by this argument, and to constrain a dark-matter–ordinary-matter interaction we must rely on our new result in Eqs. (9) and (10). There is no simple way to evaluate R in this case as the scalar charges of detector materials depend on the results of detailed calculations using specific models. We estimate R using a tree-level approximation for the scalar charge of an atom with mass number A and atomic number Z

$$q_5(A,Z) \approx (q_5^e + q_5^p)Z + q_5^n(A-Z) \ , \qquad (15)$$

where q_5^e, q_5^p, and q_5^n are the scalar charges of a free electron, proton, and neutron, respectively. Then

$$R = \frac{\sin\psi\langle Z/m\rangle + \cos\psi\langle A/m\rangle}{\sin\psi[\Delta(Z/m)] + \cos\psi[\Delta(A/m)]} \ , \qquad (16)$$

where $\psi = \arctan([q_5^e + q_5^p - q_5^n]/q_5^n)$ could range, depending on the nature of the scalar interaction, from $-90°$ to $+90°$. Our constraints on the scalar acceleration of neutral hydrogen toward the dark matter in our galaxy, assuming the expression for R given above, are shown in Fig. 2. Except for a small region around $\psi = 0$, an EP-violating acceleration toward dark matter greater than 1/10 that of gravity is ruled out by our results. Even for $\psi \approx 0$, where our sensitivity is poorest, we find $a_{ng}^{\rm DM}/a_{\rm gal}^{\rm DM} = +0.11 \pm 0.39$, which rejects by 2σ the hypothesis that $a_{\rm gal}^{\rm DM}$ is predominantly nongravitational.

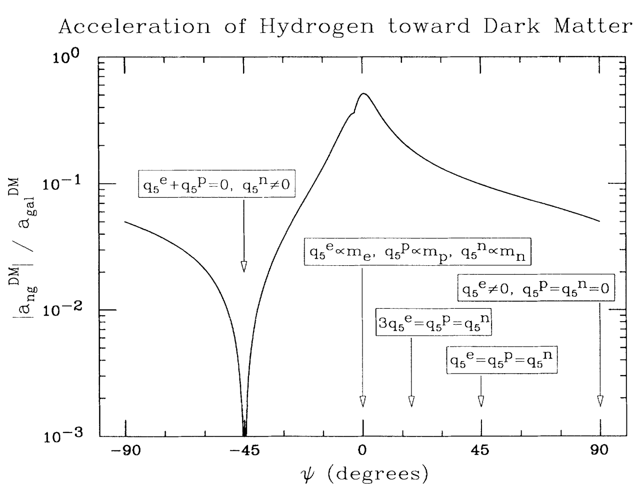

FIG. 2. 1σ constraints on the nongravitational acceleration of neutral hydrogen due to a hypothetical long-range scalar interaction with dark matter. These results assume R has the form given in Eq. (16). The vertical axis shows the ratio of the absolute value of the anomalous acceleration $|a_{ng}^{\rm DM}|$ to the total $a_{\rm gal}^{\rm DM}$. The variable on the horizontal axis specifies the scalar charge of ordinary matter.

We can obtain a different and potentially interesting constraint by considering larger-scale structures where dark matter presumably accounts for a greater fraction of our acceleration than is the case for our motion toward the galactic center. Our local group of galaxies is moving at about 600 km/s with respect to the frame in which the cosmic microwave background (CMB) is isotropic [13,14]. We estimate the corresponding acceleration by dividing this peculiar velocity by the Hubble time $t_H = 1/H_0$, where $H_0 \approx 85$ km s^{-1} Mpc^{-1} $= 2.8 \times 10^{-18}$ s^{-1} [15], and find $a_{\rm CMB} = 1.7 \times 10^{-10}$ cm/s^2. This permits a crude EP principle test for Be and Al falling in the direction of the CMB dipole:

$$\begin{aligned} \eta^{\rm CMB}({\rm Be,Cu}) &= \Delta a_{\rm CMB}/a_{\rm CMB} \\ &= (0 \pm 4) \times 10^{-2}, \\ \eta^{\rm CMB}({\rm Be,Al}) &= \Delta a_{\rm CMB}/a_{\rm CMB} \\ &= (-4 \pm 5) \times 10^{-2}\ , \end{aligned} \tag{17}$$

where $\Delta a_{\rm CMB}({\rm Be,Cu}) = (+0.2 \pm 7.3) \times 10^{-12}$ cm/s and $\Delta a_{\rm CMB}({\rm Be,Al}) = (-7.0 \pm 8.7) \times 10^{-12}$ cm/s are our constraints on differential accelerations toward the CMB dipole.

In summary, we have provided laboratory evidence for the usual assumption that gravitation is the only significant long-range interaction between dark matter and ordinary matter. There is a clear motivation for even more precise experimental limits on differential accelerations towards the galactic center and other interesting celestial sources. For example, a tenfold improvement in the precision of Δa would permit a significant EP test using the CMB dipole. We are currently planning modifications to our instrument that should yield improved results. It would also be useful to have field-theoretic calculations of R.

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[12] We define $\Delta a(x_1, x_2) = a(x_1) - a(x_2)$, where $a(x_1)$ and $a(x_2)$ are accelerations of materials x_1 and x_2 *toward* the galactic center.
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