Reanalysis of the Eötvös Experiment

Ephraim Fischbach

Institute for Nuclear Theory, Department of Physics, University of Washington, Seattle, Washington 98195

Daniel Sudarsky, Aaron Szafer, and Carrick Talmadge

Physics Department, Purdue University, West Lafayette, Indiana 47907

and

S. H. Aronson

Physics Department, Brookhaven National Laboratory, Upton, New York 11973

(Received 7 November 1985)

We have carefully reexamined the results of the experiment of Eötvös, Pekár, and Fekete, which compared the accelerations of various materials to the Earth. We find that the Eötvös-Pekár-Fekete data are sensitive to the composition of the materials used, and that their results support the existence of an intermediate-range coupling to baryon number or hypercharge.

PACS numbers: 04.90.+e

Recent geophysical determinations of the Newtonian constant of gravitation $G$ have reported values which are consistently higher than the laboratory value $G_0$. With the assumption that the discrepancy between these two sets of values is a real effect, one interpretation of these results is that they are the manifestation of a non-Newtonian coupling of the form

$$V(r) = -G_\infty \frac{m_1 m_2}{r} (1 + \alpha e^{-r/\lambda})$$

$$= V_N(r) + \Delta V(r).$$

(1)

Here $V_N(r)$ is the usual Newtonian potential energy for two masses $m_1, m_2$ separated by a distance $r$, and $G_\infty$ is the Newtonian constant of gravitation for $r \to \infty$. The geophysical data can then be accounted for quantitatively if $\alpha$ and $\lambda$ have the values

$$\alpha = -(7.2 \pm 3.6) \times 10^{-3}, \quad \lambda = 200 \pm 50 \text{ m.}$$

(2)

If $\Delta V(r)$ actually describes the effects of a new force, and is not just a parametrization of some other systematic effects, then its presence would be expected to manifest itself elsewhere as well. Recently, we have undertaken an exhaustive search for the presence of such a force in other systems. Our analysis, to be presented elsewhere, leads to the conclusion that if such a force existed it would show up at present sensitivity levels in only three additional places: (i) the $K^0\bar{K}^0$ system at high laboratory energies, where in fact anomalous effects have previously been reported; (ii) a comparison of satellite and terrestrial determinations of the local gravitational acceleration $g$; and (iii) the original Eötvös experiment which compared the acceleration of various materials to the Earth. We note that the subsequent repetitions of the Eötvös experiment by Roll, Krotkov, and Dicke and by Braginski and Panov compared the gravitational accelerations of a pair of test materials to the Sun, and hence would not have been sensitive to the intermediate-range force described by Eqs. (1) and (2). Motivated by our general analysis, we returned to the Eötvös experiment and asked whether there is evidence in their data of the presence of $\Delta V(r)$ in Eq. (1). Although the Eötvös experiment has been universally interpreted as having given null results, we find in fact that this is not the case. Furthermore, we will demonstrate explicitly that the published data of Eötvös, Pekár and

© 1985 The American Physical Society
Fekete (EPF) not only suggest the presence of a non-Newtonian coupling $\Delta V(r)$, but also strongly support the specific values of the parameters $\alpha$ and $\lambda$ in Eq. (2), which emerge from an analysis of the geometric data.

Guided by the observations that (a) $\alpha < 0$, which indicates a repulsive force, and (b) anomalous effects have been reported in the $K^0\bar{K}^0$ system as well, we consider the effects of a massive hypercharge field whose quanta (hyperphotons) have a mass $m_\gamma = \lambda^{-1} = 1 \times 10^{-9}$ eV. The exchange of a hyper photon then gives rise to a potential having the same form as $\Delta V(r)$ in Eq. (1), with $\alpha$ being related to the unit of hypercharge $f$ by

$$f^2 = \frac{\alpha}{\alpha + 1},$$

where $m_\gamma$ is the proton mass. Consider the relative accelerations of two objects 1 and 2 with masses $m_{1,2}$ and hypercharges (or baryon numbers) $B_{1,2}$. Because of the presence of $\Delta V(r)$ the accelerations $a_{1,2}$ of these objects to the Earth will no longer be the universal Newtonian value $g$, but will differ by an amount $\Delta a = a_1 - a_2$ given by

$$\frac{\Delta a}{g} = f^2 \frac{\epsilon(R/\lambda)}{G_0 m_\gamma^2} \left( \frac{B_1}{\mu} - \frac{B_2}{\mu_2} \right).$$

Here $\mu_i$ denotes the mass $m_i$ in units of atomic hydrogen, with $m_H = m \left( ^1H^1 \right) = 1.00782519(8)$ u, and we can take $B_\phi/\mu_\phi \approx 1$ for present purposes. $\epsilon(R/\lambda)$ arises from integration of the intermediate-range hypercharge distribution over the Earth, assumed to be a uniform sphere of radius $R$, and is given by ($x = R/\lambda$)

$$\epsilon(x) = \frac{3(1 + x)}{x^3} e^{-x}(\cosh x - \sinh x).$$

For $\lambda \to \infty$, $\epsilon(0) \to 1$, and (4) reduces to the result of Lee and Yang. However, the limit of interest to us here is $x \gg 1$ in which case $\epsilon(x) \approx 3/2x$.

Equation (4) can now be compared directly to the results of EPF, where in their notation $\Delta a/g = \kappa_1 - \kappa_2 = \Delta \kappa$. Table I gives $\Delta \kappa$ for each of the nine pairs of materials measured by EPF, exactly as their result is quoted on the indicated page of Ref. 6. For each of the pairs in which the composition of both samples can be established (see discussion below), we also tabulate $\Delta (B/\mu) = B_1/\mu_1 - B_2/\mu_2$ using the data of Ref. 10. In the computation of $B/\mu$ for each material, care has been taken to average over all the isotopes of each element, and to weight the contribution of each element in a compound according to the appropriate chemical formula. Among the substances appearing in Table I, Cu, Pt, and water require no further description, crystalline copper sulfate has the formula CuSO$_4$·5H$_2$O, and the CuSO$_4$ solution consisted of 20.61 g of crystalline copper sulfate in 49.07 g of water. By contrast, magnalium is an aluminum-magnesium alloy of varying composition, with typical Al:Mg ratios being in the range 95:5–70:30. Although the exact composition of the magnalium alloy used by EPF is not given, $B/\mu$ for Al and Mg are very nearly equal so that $B/\mu$ for any magnalium alloy would fall in the narrow range

$$1.00845 \text{ (pure Mg)} \leq B/\mu \text{ (magnalium)} \leq 1.00851 \text{ (pure Al)}.$$  

The results in Table I assume a composition Al:Mg = 90:10, which is one of the more common alloys. The remaining material whose composition can be established with some certainty is asbestos, since 95% of asbestos production is a fibrous form of the mineral serpentine called chrysotile, whose chemical formula is Mg$_3$Si$_2$O$_5$(OH)$_4$. In addition to measuring the relative acceleration of various pairs of materials, EPF also compared the accelerations of the reactants before and after the chemical reaction

$$2\text{Ag}_2\text{SO}_4 + 2\text{FeSO}_4 \rightarrow 2\text{Ag} + 2\text{Fe}_2(\text{SO}_4)_3.$$  

Table I. Summary of EPF results for $\Delta \kappa$, and page quoted from Ref. 6, along with the computed values of $\Delta (B/\mu)$. Ag-Fe-SO$_4$ refers to the reactants before and after the chemical reaction described by Eq. (7).

<table>
<thead>
<tr>
<th>Materials compared</th>
<th>Page quoted</th>
<th>$10^3 \Delta \kappa$</th>
<th>$10^3 \Delta (B/\mu)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu-Pt</td>
<td>37</td>
<td>$+0.4 \pm 0.2$</td>
<td>$+0.94$</td>
</tr>
<tr>
<td>Magnesium-Pt</td>
<td>34</td>
<td>$+0.4 \pm 0.1$</td>
<td>$+0.50$</td>
</tr>
<tr>
<td>Ag-Fe-SO$_4$</td>
<td>39</td>
<td>$0.0 \pm 0.2$</td>
<td>$0.00$</td>
</tr>
<tr>
<td>Asbestos-Cu</td>
<td>47</td>
<td>$-0.3 \pm 0.2$</td>
<td>$-0.74$</td>
</tr>
<tr>
<td>CuSO$_4$·5H$_2$O-Cu</td>
<td>44</td>
<td>$-0.5 \pm 0.2$</td>
<td>$-0.86$</td>
</tr>
<tr>
<td>CuSO$_4$(solution)-Cu</td>
<td>45</td>
<td>$-0.7 \pm 0.2$</td>
<td>$-1.42$</td>
</tr>
<tr>
<td>Water-Cu</td>
<td>42</td>
<td>$-1.0 \pm 0.2$</td>
<td>$-1.71$</td>
</tr>
<tr>
<td>Snakewood-Pt</td>
<td>35</td>
<td>$-0.1 \pm 0.2$</td>
<td>?</td>
</tr>
<tr>
<td>Tallow-Cu</td>
<td>48</td>
<td>$-0.6 \pm 0.2$</td>
<td>?</td>
</tr>
</tbody>
</table>
Since $B/\mu$ is the same before and after the reaction, $\Delta \kappa$ should be zero in this case, which is indeed what EPF found. The remaining materials used by EPF are schlagentholz (snakewood) and tallow (tallow, grease, suet, etc.) whose exact compositions cannot be established. In particular, the amount of water in each of these is unknown, and since water has a relatively low value of $B/\mu$, the effective value of $B/\mu$ for the sample could vary over a wide range depending on its water content.

In Fig. 1 we plot the measured value of $\Delta \kappa$ versus the computed values of $\Delta(B/\mu)$ using the data given in Table I. We see immediately that the EPF data clearly exhibit the linear relationship between $\Delta \kappa$ and $\Delta(B/\mu)$ expected from Eq. (4). Furthermore, the solid line resulting from a least-squares fit to the data passes through the origin, as it should if Eq. (4) holds. Finally, the slope of the line is in remarkably good agreement with the value expected from the parameters in Eq. (2) which arise from the geophysical data. Specifically, we find from the least-squares fit that the equation of the line is

$$
\Delta \kappa = a \Delta(B/\mu) + b,
$$

where $a$ is the electric charge in Gaussian units. This should be compared to the value derived from the geophysical data in Eq. (2),

$$
[f^2 \epsilon(R/\lambda)]_{\text{geophysical}} = (2.8 \pm 1.5) \times 10^{-43} e^2. \quad (10)
$$

The agreement between these two results is surprisingly good, particularly in view of the simple model of the Earth that has been used in deriving (4) and (9). If $\lambda$ is in fact on the order of 200 m, then the details of the local matter distribution will clearly modify the functional form of $\epsilon(R/\lambda)$, and could lead to improved agreement between (9) and (10). If the potential in Eqs. (1) and (2) describes a coupling to hypercharge, as we have assumed, then it should also give rise to an anomalously strong dependence of the fundamental $K^0\bar{K}^0$ parameters such as the $K_L-K_S$ mass difference $\Delta m$, the $K_S$ lifetime $\tau_S$, and the $CP$ nonconserving parameter $\eta_{+-}$. Here the intermediate-range nature of the coupling is crucial in understanding the effects that arise. As we discuss in Ref. 3, the specific values of $\alpha$ and $\lambda$ in (2), which account for both the geophysical data and the Eötvös results, may also explain the kaon data as well, both qualitatively and quantitatively.

The possibility that the three effects that we have discussed do in fact have a common origin can be directly tested in several ways. To start with, the Eötvös experiment itself should be repeated with greater sensitivity, and with a variety of materials whose precise composition is known. As has been noted elsewhere, the composition dependence of the Eötvös anomaly is $\eta_{+-}$. $\Delta a/g$ can be used to rule out various possible explanations of this effect. In particular, we show in Ref. 3 that neither a coupling to lepton number nor a recently proposed model of Lorentz noninvariance can account for the data of Ref. 6. While a repeat of the Eötvös experiment with better sensitivity may be possible with modern techniques, it may be more practical simply to compare the times of flight of different test masses dropped from the same height, in an updated version of the Galileo experiment. To achieve a sensitivity sufficient for our purposes, say $\Delta a/g = 10^{-10}$, would require measurement of the time of flight to within 0.1 ns over a distance of 10 m which is within the realm of feasibility. In addition, one can attempt to improve the measurement of $\Delta g$, the difference between the locally measured value of $g$ and that implied by satellite data. Evidently satellite measurements would not be sensitive to $\Delta V(r)$ in (1) and (2), whereas local measurements would, and it follows from (1) and (2) that $\Delta g/g$ should be approximately $2 \times 10^{-7}$. An analysis of the available data by Rapp gives a value $\Delta g/g \approx (6 \pm 10) \times 10^{-7}$, but the prospects for improving this result are somewhat uncertain. Finally, if we take seriously the existence of a hypercharge field, then one can search directly for hyperphotons $\gamma^*$ via their cosmological effects, and in

![FIG. 1. Plot of $\Delta \kappa$ vs $\Delta(B/\mu)$ using the data in Table I. Ag-Fe-SO$_4$ refers to the reactants before and after the chemical reaction described by Eq. (7). The solid line represents the results of a least-squares fit to the data.](image-url)
decays such as $K^0 \to 2\pi + \gamma_\gamma$. Following Weinberg, we note that the branching ratio for this mode is
\begin{equation}
\frac{\Gamma(K^0 \to 2\pi + \gamma_\gamma)}{\Gamma(K^0 \to 2\pi)} = \left( \frac{f^2}{m} \right) \left( \frac{E_{\max}^2}{8\pi^2} \right),
\end{equation}
where $E_{\max} << m_K$ is the maximum hyperphoton energy detected. For $f$ and $m_Y$ as given in (2) and (3), and $E_{\max} = 100$ MeV, the branching ratio is $6 \times 10^{-9}$. This is safely below the level where hyperphotons could have been detected in the course of other experiments, but at the same time is large enough so that a direct search for this mode may prove possible. From a cosmological point of view, hyperphotons would act as a massive but very weakly interacting constituent of interstellar space, and could thus help account for the missing mass of the Universe.

We are indebted to Frank Stacey for communicating the results in Eq. (2) prior to publication, and to Peter Buck for translating parts of Ref. 6. We also wish to thank Mark Haugan, Wick Haxton, Ernest Henley, Fred Raab, and Richard Rapp for helpful conversations. One of us (E.F.) wishes to thank the Institute for Nuclear Theory at the University of Washington for its hospitality during the course of the research. This work was supported in part by the U. S. Department of Energy.

Note added.—R. H. Dicke (private communication) has raised with us the question of whether some systematic effect in the EPF experiment could simulate the observed correlation between $\Delta \kappa$ and $\Delta(B/\mu)$. He proposed an interesting model in which thermal gradients could lead to a correlation between $\Delta \kappa$ and the quantity $(a + b/p_1 - c/p_2)$, where $p_1, p_2$ are the densities of the samples and $a$, $b$, and $c$ free parameters. We have investigated this model, and others involving $\rho_1, \rho_2$, and have found that none of these show a correlation with $\Delta \kappa$. These results will be presented in detail in Ref. 3, where we will also show that they are a consequence of two special properties of $B/\mu$: (1) it has an anomalously low value for hydrogen, and (2) it has a maximum near Fe and is lower toward either end of the Periodic Table. We wish to thank Professor Dicke for stimulating us to investigate this question.

\begin{enumerate}
\item On sabbatical leave from (1985–1986) from Purdue University, West Lafayette, Ind. 47907.
\item F. D. Stacey, private communication.
\item E. Fischbach, D. Sudarsky, A. Szafer, C. Talmadge, and S. H. Aronson, to be published.
\item R. H. Siche, Sci. Am. 205, 84 (1961); P. G. Ropp R. Krotkov, and R. H. Dicke, Ann. Phys. (N.Y.) 26, 442 (1964). These authors have pointed out various inconsistencies in a repetition of the original Eötvös experiment by Renner, and hence we have ignored Renner’s results.
\item V. Braginskii and V. I. Panov, Zh. Eksp. Teor. Fiz. 61, 873 (1971) [Sov. Phys. JETP 34, 463 (1972)].
\item It is interesting to note that on p. 65 of Ref. 6 EPF summarize their data as if all the indicated samples were actually measured against a Pt standard, notwithstanding the fact that in most of the measurements the actual standard was Cu. The effect of combining, say, $\Delta \kappa$(H2O-Cu) and $\Delta \kappa$(Cu-Pt) to infer $\Delta \kappa$(H2O-Pt) is to reduce the magnitude of the observed nonzero effect from $5\sigma$ to $2\sigma$. Any suggestion of a nonzero effect was further reduced by choosing Pt rather than Cu as the standard since, had the opposite choice been made, the signs of all the nonzero $\Delta \kappa$ would have been the same, and might thus have pointed to a possible systematic effect.
\item Improvements in the Eötvös and Galileo experiments will be the subject of a separate paper.
\item R. H. Rapp, private communication.
\end{enumerate}
ERRATA


In Eq. (17), the $k^+_k$ should be $q^+_k$. The following clause should read, “where the relation $\exp(i2\pi h^+_k/k_0) = \exp(i\pi \sum_{n=1}^{\delta} \lambda_n)$ has been used.”


The left-hand side of Eq. (1) should read $(1 + \delta_{n-1}) \ln \eta_j(\beta)$. 
Comment on the Sign in the Reanalysis of the Eötvös Experiment

In a recent Letter to this journal Fischbach et al. reanalyzed the measurements of Eötvös et al. and found an intriguing correlation between the effective gravitational mass and the baryon number of matter.

Fischbach et al. propose the existence of a fifth force mediated by hyperphotons coupled to the baryon number or hypercharge. This vector force is repulsive between matter objects. The authors claim that the Eötvös data support this conjecture.

Here it is pointed out that there is a sign error in Ref. 1 in Eqs. (4) and (9) for the predicted correlation between the gravitational acceleration and baryon number according to the hyperphoton force. (In a previous article the sign was given correctly.)

To see this, compare the gravitational acceleration of water and copper. Water has a smaller nuclear binding energy than copper and therefore a smaller ratio of baryon number and mass. This leads to a smaller coupling to the hyperphoton and thus a weaker repulsion from the Earth. Since this repulsion compensates the gravitation, water will have a larger effective gravitational mass than copper, according to the hyperforce theory.

Consider next the Eötvös data which are quoted correctly in Fig. 1 and Table 1 of Ref. 1. It is important to specify the definition of the sign of \( \kappa \), and this is given on p. 15 of Ref. 2:

\[
G' = G (1 + \kappa).
\]

Here \( G \) is gravity for standard matter, e.g., water, and \( G' \) is gravity of another substance, e.g., Cu, characterized by \( \kappa \). The sign convention of \( G \) is unimportant; it is the sign of \( \kappa \) relative to 1 which matters. On p. 42 in Ref. 2 it is reported that

\[
\kappa_{\text{water}} = \kappa_{\text{Cu}} = (-0.010 \pm 0.002) \times 10^{-6}.
\]

i.e., water has less gravitational mass than Cu, as indeed quoted in Ref. 1.

In this context it must be realized that Eötvös was a geophysicist, and that his apparatus was mainly used to measure the gravitational gradients in mountains. Eötvös was trained to indicate the sign of the measurements, since this is essential when making measurements in mines in order to know in which direction to search for ore.

To summarize, Eötvös has measured that water falls more slowly than copper, whereas the hyperforce theory predicts the opposite.

If the Eötvös data are correct we can conclude that there is a new attractive force between matter objects coupled to baryon number. This new interaction is mediated by spin-2 particles (or spin-0 particles).

We notice that this disagrees with the interpretations of the geophysical measurements reported by Fischbach et al.,1 and by Holding, Stacey, and Tuck,4 which hint at an extra repulsive force. Of course, the presence of the geophysical data does not allow one to change the sign of the Eötvös anomaly according to the interpretation in Ref. 1.

I acknowledge conversations with S. H. Aronson and E. Fischbach.

Hans Henrik Thodberg
Niels Bohr Institute
DK-2100 Copenhagen, Denmark

Received 24 January 1986
PACS numbers: 04.90.+e

3E. Fischbach et al., Phys. Rev. D 32, 154 (1985), Eqs. (3) and (8).

The sentence beginning on line 11 of the right-hand column on page 921 which reads, “The deviation counting rate is very small and the combination of counting rates plotted in Fig. 2 is very sensitive to background” should be replaced by “The deviation for the highest-energy points occurs near the end point where the $\beta$-decay counting rate is very small and the combination of counting rates plotted in Fig. 2 is very sensitive to background.”


A limitation in the extrapolation procedure used to calculate the trapped charge $Q_0$ and $Q_0$ at zero delay time leads to unrealistically high values of this parameter for the high-temperature ($\geq 350$ K) data in Figs. 3 and 4.

Experimental measurements of trapped charge were restricted to delay times greater than a few tenths of a second. At high temperatures, this resulted in most of the charge being released prior to the measurement point [see Fig. 2(a)]. To calculate $Q_0$ or $Q_0$, the model of Fig. 2(b) was used to correct the data to zero delay time. The multiplication factor thus obtained is strongly dependent upon the value of trap depth, $E_0$, to the extent that an inaccuracy of a few hundredths of an electronvolt produces an error in $Q_0$ or $Q_0$ of several orders of magnitude at 400 K.

The above effect resulted in calculated values of $Q_0$ and $Q_0$ in excess of those realistic for the experimental conditions. Note, however, that (a) data taken below about 320 K are not subject to the above problem, since only a limited amount of charge is released in the initial delay period [see Fig. 2(a)], and (b) the shapes of the high-temperature curves in Figs. 3 and 4 are unaffected by any computational error, since a constant multiplying factor was employed for all data taken at a particular temperature. Therefore, other derived parameters, such as the time constant for annealing obtained from the data in Fig. 4, remain unaltered.


The symbol $\delta$ in Eq. (1) should be $\rho$.


The formula on the bottom of column 1 should read

$$\kappa_{\text{water}} - \kappa_{\text{Cu}} = (-0.010 \pm 0.002) \times 10^{-6}.$$ 


In the sentence following Eq. (5), “... for $r < r_m$ is equivalent...” should read “... for $r < r_m/2$ is equivalent...”

In Table I, the value of $\rho_4 x^3$ at $kT/\epsilon = 2.74$ reads “(1.150)” and should read “(1.179)”.


On page 78, opening paragraph, the sentence “This analysis does not simplify the mathematics but yields new insights...” should read “This analysis not only simplifies the mathematics but also yields new insights...”

On page 81, in Ref. 7, “$\theta + 2\pi$” should read “$\theta + 2\pi$.”
Fischbach et al. Respond: Thodberg\(^1\) and also Hayashi and Shirafuji\(^2\) raise a valid question about the signs in Eq. (4) and the subsequent equations in our paper.\(^3\) We have defined \(g = |g| = G_0 M_b / R^2_b\), so that Eq. (4) is correct as it stands for the assumed repulsive force. On the other hand, these authors correctly point out that the Eötvös-Pekár-Fekete (EPF) results, taken at face value, imply that the force actually is attractive, contrary to what we have assumed.

We show elsewhere\(^4\) that one cannot in fact deduce from the EPF data whether the force is attractive or repulsive. The reason for this is that in the presence of an intermediate-range force, local horizontal mass inhomogeneities (e.g., buildings or mountains) can be the dominant source in the Eötvös experiment.\(^4\) Their effects can be more important than those arising from the Earth as a whole, even though the Earth is the main source of the gravitational force. For this reason one cannot infer either the magnitude or the sign of the EPF anomaly in the absence of a more detailed knowledge of the local matter distribution at the time of the experiment than we presently have available.

To see why this is the case, let us consider the effects of a building and its basement on the Eötvös balance. We approximate the former by a sphere of mass \(M\) and radius \(R\), and the latter by a sphere of missing mass \(M'\) and radius \(R'\). The centers of each sphere are located at angles \(\phi\) and \(\phi'\) relative to the horizontal, and the experiment is performed at a latitude \(\theta\). Finally, we locate these spheres to the north of the apparatus (itself oriented east to west), since we know from the EPF description of the location of their experiment that they were in a room facing south. Then the component of the net torque \(\tau_{\text{net}}\) about the fiber axis \(\hat{x}_3\) is given by

\[
\tau_{\text{net}} = m_1 I \left( \frac{B_1}{\mu_1} - \frac{B_2}{\mu_2} \right) \left[ a \sin \theta \frac{y + y_{\text{building}} \cos (\phi + \beta) - y'_{\text{hole}} \cos (\phi' + \beta)}{g} \right],
\]

where \(a\) is the Earth's centrifugal acceleration, \(\beta \approx \beta_1 \approx \beta_2\) is the angle that a plumb line makes (for mass \(1,2\)) with the vertical, and \(2I_1\) is the length of the torsion bar. The hypercharge fields due to the Earth and the building are denoted by \(y\) and \(y'\), respectively, with \(y = \xi (p_{\text{local}} / \rho) (B / M) \epsilon (R / \lambda) g\), \(y' = \xi g'\) (where \(\xi = f^2 / G m_1^2\), and \(g\) and \(g'\) are respectively the magnitudes of the gravitational accelerations towards the Earth and the building), and all other notation is as in Refs. 3 and 4. For typical institutional buildings, \(M \approx (2-5) \times 10^6\) kg, \(M' \approx (8-20) \times 10^6\) kg, and from the known dimensions of the basement above which the EPF experiment took place, \(M' \approx 14 \times 10^6\) kg, on the assumption of an average local mass density \(\rho_{\text{local}} = 2750\) kg/m\(^3\). The significance of the basement is that it acts as a “hole” in the otherwise uniform matter distribution of the Earth, whose effects are described by the first term in Eq. (1). Thus its effects could contribute with a sign opposite to that of the Earth as a whole, and can be substantially larger. If the picture of the matter distribution given in Ref. 4 were correct, then the actual EPF data would indeed correspond to a repulsive force.

The simple picture described above should not be taken too literally, since there were in fact other (perhaps more important) sources of local matter inhomogeneities. However, the preceding discussion makes it clear that local mass anomalies can be important because the magnitude of the horizontal hypercharge force component may be enhanced by as much as a factor of \(1/\sin \beta\) with respect to that originally modeled in Ref. 1. Moreover, the sign of the horizontal component can be either positive or negative depending on the location of the anomalies relative to the apparatus. These arguments make it clear that the only unambiguous consequence of the intermediate-range coupling to baryon number or hypercharge is the pattern of points along a line plotting \(\Delta \kappa\) vs \(\Delta (B/\mu)\), and not the sign or magnitude of the corresponding slope.

Ephraim Fischbach
Physics Department
University of Washington
Seattle, Washington 98195

Daniel Sudarsky, Aaron Szafer, and Carrick Talmadge
Physics Department
Purdue University
West Lafayette, Indiana 47906

S. H. Aronson
EP. Division, CERN
Geneva, Switzerland

Received 28 February 1986
PACS numbers: 04.90.+e

Comment on "Reanalysis of the Eötvös Experiment"

Fischbach et al. present an analysis of the Eötvös, Pekár, and Fekete (EPF) data from which they suggest the presence of a non-Newtonian coupling to baryon number (i.e., hypercharge). We find two flaws: (a) They misinterpret or omit some of the EPF data and (b) they reject the work of János Renner. To make Fischbach et al.'s Eq. (10) consistent with Eq. (9) for a uniform-density Earth would require that \( \alpha \) be increased from \(-0.0072 \pm 0.0036\) to \(-0.11\), or by 28 times the quoted uncertainty. Allowing for the Earth's lower surface density would require twice this increase.

EPF used a number of composite test bodies in which a brass container held the material of interest, and correct their data to account for use of these brass containers. When we take the raw \( \Delta \kappa \) data of EPF and calculate the values of \( B/\mu \) including these brass containers, we find that four of the seven points used by Fischbach et al. are moved toward the origin by varying amounts (along the fitted line of Fischbach et al.).

The tallow-copper and snakewood-platinum points were omitted by Fischbach et al. on the grounds that the composition of the first material was unknown. Schlangenholz (lignum vitae) is a wood, and all woods are composed primarily of cellulose (a known polysaccharide) and lignin (a known two-amino-acid copolymer). The Talg was purified beef or mutton tallow, which are known fats (triglycerides). Most serious is the unnoted omission of a datum. EPF measured \( \Delta \kappa \) for a 0.1-g glass vial containing 0.1 g of RaBr\(_2\) in a 25.2-g brass container versus a 25.4-g platinum cylinder. This test body was 99% brass by mass, so that this test amounts to a brass-Pt test. In fact, \( \Delta (B/\mu) \) here differs from the \( \Delta (B/\mu) \) of Cu-Pt by only \( 0.006 \times 10^{-3} \), yet its value of \( \Delta \kappa \) differs by some \( 3.5 \sigma \) from the \( \Delta \kappa \) of the Cu-Pt datum.

Fischbach et al. rejected the work of Renner because of "various inconsistencies" noted by Roll, Krotkov, and Dicke (RKD). On the basis of examining Renner's original data, RKD suggest that his standard deviations should be multiplied by a factor of 3. RKD also point out the anomalously large ratio of his (corrected) standard deviations to the deviations of his means. Though these issues cannot be resolved unambiguously "after the fact," we nevertheless feel these data should not be wholly ignored in regards to the \( \Delta \kappa \) values which can be derived from them.

Figure 1 shows all \( \Delta \kappa \) data from Refs. 2 and 3. The line is from Fischbach et al. for comparison. (The \( \sigma \) values for Renner's data have been increased by the factor of 3 suggested by RKD.) The experimental data do not appear to support Fischbach et al. We are looking at various possible contemporary Eötvös and Galileo tests.

We thank Dr. D. Bartlett, Dr. P. Bender, and Dr. C. Wieman for helpful discussions and the National Bureau of Standards, Sensor-Technology Division of Belvoir RD&E Center, and The Air Force Geophysics Laboratory for support.

Paul T. Keyser, Timothy Niebauer, and James E. Faller
Joint Institute for Laboratory Astrophysics
University of Colorado and National Bureau of Standards
Boulder, Colorado 80309

Received 6 February 1986
PACS numbers: 04.90.+e

4E. Luschin, Berg-Hüttenmänn. Jahrb. 38, 87 (1890), says that Asbest is fibrous amphibole (tremolite to actinolite), so that \( B/\mu - 1 = (8.470 \pm 0.096) \times 10^{-3}, \) 2.6 \( \sigma \) larger than \( B/\mu - 1 \) for chrysotile. Uncertainties on \( B/\mu \) (Asbest, Schlangenholz, Talg) cover the full range of values.
7Meyers Lexikon (Bibliographisches Institut, Leipzig, 1929); see "Talg."
8Ref. 6, Vol. 1, pp. 348–349.
9Ref. 2, pp. 59–61.
10Ref. 1, p. 6, footnote 7.
Fischbach et al. Respond: In the accompanying Comment\(^1\) Keyser, Niebauer, and Faller (KNF), claim that we\(^2\) misinterpreted the Eötvös-Pekár-Fekte (EPF) data by using the results quoted by EPF rather than the raw $\Delta \kappa$ values. They fail, however, to note that one can equivalently use either the raw data or the final corrected data for the investigation of a correlation with $B/\mu$, since $(B/\mu)_{\text{raw}} = (B/\mu)_{\text{Cu}}$. EPF corrected their data (in this case, legitimately) by assuming that the brass container did not contribute to the acceleration anomalies. Furthermore, even if one were studying a property in which brass was distinctly different from copper, only the $\text{H}_2\text{O}-\text{Cu}$ datum would require special treatment. This is because for all of the other comparisons in which the sample was contained in a brass container, the Cu reference was also contained in a brass cylinder similar in size to that used to hold the sample. Moreover, a fit to the data with the brass vials yields very nearly the same parameters as were obtained in Ref. 2.

KNF quote $B/\mu$ for various materials which differ somewhat from ours. For asbestos, KNF correctly note that it can contain a large amount of actinolite. However, the closest source of asbestos to Hungary would have been the Asbest region in the Ural mountains, which \(^*\)as far as is known, produces only chrysotile.\(^*\) which is what we used in Ref. 1.

KNF note that the RaBr\(_2\) datum was not included. The reason for this is that in the same section of the paper in which EPF discuss their measurements of $\Delta \kappa$ for RaBr\(_2\), they also discuss a series of experiments which demonstrate the various anomalous effects which can arise from thermal heating of the apparatus by the RaBr\(_2\) sample. It was for this reason that this datum was excluded from the overall analysis in Ref. 1. Furthermore, a subsequent recheck of the EPF paper has revealed a typographical error in the sign EPF quote for this value. With the corrected sign $\Delta \kappa$ is now $(+1 \pm 2) \times 10^{-9}$, and this result agrees with the value obtained for Cu-Pt within the quoted errors. One can infer from this comparison that their apparatus was not excessively sensitive to thermal effects.

KNF also comment that the Renner data should be included along with the EPF data in a search for a possible correlation with $\Delta (B/\mu)$, although they do not give any compelling reasons for our disregarding the criticism of these data by Roll, Krotkov, and Dicke\(^4\) (RKD). RKD’s primary criticism was that Renner’s quoted errors “are not consistent with his claimed $\frac{\Delta}{\Delta}$ scale-division reading error.” Second, RKD also note that Renner incorrectly evaluated his errors, which RKD give as a possible explanation of the inconsistency between Renner’s quoted errors and his scale-reading accuracy. Thirdly, RKD note that the mean values are too small compared even to his quoted errors. Finally, we note that even if Renner’s data were completely valid, it would still be incorrect to plot them on the same graph with those of EPF. The reason for this is that, as we\(^5\) and others\(^6\) have noted, the magnitude and sign of the slope $\Delta \kappa/\Delta (B/\mu)$ that one obtains from a particular Eötvös experiment is highly sensitive to the local matter distribution. The EPF and Renner experiments were not in fact performed in the same location.\(^7\) Hence if the latter were carried out in a relatively symmetric environment, it could very well be the case that Renner would have been expected to see an (almost) null result.

The apparent discrepancy between the geophysical and the EPF data can be resolved by noting that the effect of the nearby matter distribution is to change both the sign and magnitude of the Eötvös anomaly compared to what one obtains from the naive spherical model of the Earth used in Ref. 2. Moreover, since (9) and (10) of Ref. 2 effectively involve the product $\alpha \lambda$, these equations can be made consistent by an increase of either $\lambda$ or $\alpha$. Recent work of Holding, Stacey, and Tuck\(^8\) indicates that the value of $\lambda$ implied from their data is so uncertain that there is at present no conflict in the magnitudes of the effects implied by the EPF data.

E. Fischbach,\(^1,2\) D. Sudarsky,\(^2\) A. Szafer,\(^2\) C. Talmadge,\(^2\) and S. H. Aronson\(^1,4\)

1Department of Physics
University of Washington
Seattle, Washington 98195

2Department of Physics
Purdue University
West Lafayette, Indiana 47907

3Brookhaven National Laboratory
Upton, New York 11973

4CERN
1121-Geneva 23, Switzerland

Received 17 March 1986
PACS numbers: 04.90.+e

\(^{1}\)Paul T. Keyser, Timothy Niebauer, and James F. Faller, preceding Comment [Phys. Rev. Lett. 56, 2425 (1986)].


\(^{5}\)C. Talmadge, S. H. Aronson, and E. Fischbach, University of Washington Report No. 40048-12-N6, 1986 (to be published).


\(^{7}\)J. Barnothy, private communication.

Alternative Explanations of the Eötvös Results

Our recent reanalysis\(^1,2\) of the experiment by Eötvös, Pekár, and Fekete\(^3\) (EPF) has uncovered in the EPF data a correlation between the fractional acceleration difference \(\Delta \kappa\) and the quantity \(\Delta (B/\mu)\), where \(B\) is baryon number and \(\mu\) is the mass in units of \(m(\text{H})\). Although this correlation agrees with what one would expect from the presence of an intermediate-range force whose source is baryon number of hypercharge, the possibility remains that the EPF results could be explained in terms of conventional physics. The only alternative model we know of at present which has a serious chance of explaining these results is the "thermal-gradient" model of Chu and Dicke\(^4\) (CD), and for this reason the CD model deserves to be taken seriously. In what follows we examine the strengths and limitations of the CD model in light of the EPF data.

The premise of this model is that if horizontal thermal gradients were present in the EPF apparatus, they could produce a gentle "breeze" which could exert a force on the samples being compared. Since the samples, or the containers they were in, had different physical dimensions, the forces exerted on opposite sides of the apparatus would not be equal, and a net torque could result. In practice, this would lead to a correlation between \(\Delta \kappa\) and \(\Delta (1/\rho)\) or \(\Delta S\), where \(\rho\) is the density of the sample and \(S\) is the cross-sectional surface area of the sample or its container. This nicely illustrates how a systematic effect can appear to depend on a property of the samples, such as \(1/\rho\).

It is useful to picture any acceptable alternative to the baryon-number or hypercharge hypothesis as satisfying two separate criteria: (i) To start with, the mechanism in question should have the property that the torque which it produces must change when the EPF apparatus is rotated through 180\(^\circ\); (ii) the torque produced by the alternative mechanism must not only be composition dependent, but also must vary from one material to another in a manner that (at least approximately) simulates a variation with \(B/\mu\). The significance of the first criterion, when applied to the CD model, is to suggest that if a thermal gradient (or breeze) is to simulate the effects of a matter distribution (e.g., the presence of a mountain or building), it must produce a force which is similarly constant on average temporally relative to the apparatus. However, it is unclear how any likely heat source (e.g., a window or radiator) would always produce a gradient with both a fixed direction and fixed magnitude, independent of time of day or year over the period of months or years that the experiment took place. The challenge to the CD model arising from the second criterion is to explain adequately the Pt data, which tend not to fit that well, irrespective of how the model is formulated. As CD correctly point out, there is a clear suggestion of a correlation between \(\Delta \kappa\) and \(\Delta S\) or \(\Delta (1/\rho)\) evidenced by the double-torsion-balance data alone, particularly for those comparisons carried out using EPF's method III, which happened not to involve Pt. The reason for this is illuminating, and provides an insight into other possible correlations as well. If we examine a plot of \(B/\mu\) as a function of atomic number \(Z\), we see that for the EPF samples \(B/\mu\) is an approximately monotonically increasing function of \(Z\), provided we exclude Pt. It follows that since \(B/\mu\) does in fact correlate with \(\kappa\), so will any other nearly monotonically changing variable, provided that the Pt data are excluded. Hence it is precisely these data which test the characteristic shape of \(B/\mu\) as a function of \(Z\), and which thus discriminate between a correlation with \(B/\mu\) and one involving some other variable. It follows that the suggestion of an approximate correlation between \(\Delta \kappa\) and \(\Delta (1/\rho)\) is not surprising, since \(-1/\rho\) is also an approximately increasing function of \(Z\) for the substances studied by EPF.

In summary, the CD model is very clever and sufficiently promising to warrant more detailed study, should ongoing experiments fail to confirm the original EPF results. The issues that it must address more fully are mechanisms for producing a temporally constant thermal gradient over a long period of time, and the behavior of the Pt data.

E. Fischbach,\(^{(1),(2),(a)}\) D. Sudarsky,\(^{(1)}\) A. Szafer,\(^{(1)}\) C. Talmadge,\(^{(1)}\) and S. H. Aronsen\(^{(3),(4),(b)}\)

\(^{(1)}\)Department of Physics, Purdue University
West Lafayette, Indiana 47907
\(^{(2)}\)Department of Physics, University of Washington
Seattle, Washington 98195
\(^{(3)}\)Brookhaven National Laboratory
Upton, New York 11973
\(^{(4)}\)EP Division, CERN
CH-1211 Geneva 23, Switzerland

Received 7 July 1986
PACS numbers: 04.90.+e

\(^{(a)}\)Present address: Department of Physics, Purdue University, West Lafayette, IN 47907.
\(^{(b)}\)Present address: Brookhaven National Laboratory, Upton, NY 11973.
Comment on “Reanalysis of the Eötvös Experiment”

To the zeroth order, the Earth is a sphere held together by gravitation, and the plumb line is directed toward the center of the sphere. To the first order, the Earth is an ellipsoid of revolution held together by gravitation but deformed by the centrifugal forces of its rotation, and the plumb line is not, in general, directed toward the center of the ellipsoid. The ellipsoid is an equipotential surface: Horizontal gravitational forces (northward in Hungary) on passive gravitational masses are exactly balanced by opposing centrifugal forces (southward in Hungary) on inertial masses. The plumb line is normal to this surface. If the ratio of passive gravitational to inertial masses differed between two materials, say copper and platinum, then proof masses of copper and platinum would have different plumb lines and therefore different ellipsoids. The basic concept of the Eötvös experiment is that if the copper and platinum proof masses of a torsion balance are aligned in an east-west direction (along the intersection of the copper and platinum ellipsoids) and the balance is allowed to rotate, then each proof mass will be able to drop with respect to its own ellipsoid until the gravity and elastic torques of the mechanism are balanced. Eötvös, Pekár, and Fekete (EPF) and Renner performed the experiment for various pairs of proof masses and concluded that the ratio of inertial to passive gravitational mass is independent of the composition of the mass.

Fischbach et al. reanalyzed the EPF data and concluded that the results are sensitive to the proof-mass compositions and that the data support the existence of an intermediate-range (~200 m) coupling to baryon number. Keyser, Niebauer, and Faller contend that the results are not sensitive to the proof-mass compositions, and I contend that in the absence of local mass inhomogeneities the Eötvös experiment is quite insensitive to any intermediate-range (small compared with the Earth’s radius) coupling of any nature. The effect of a local coupling would be to change the magnitudes of the downward forces on the proof masses and on the torsion balance wire, but it would not change the direction of the plumb lines for different composition proof masses; in effect there would be no horizontal “fifth force” component, so the torsion balance would sense nothing. This argument does not preclude the possible existence of an intermediate-range coupling, such as is hinted at by the consistent discrepancy between the Newtonian gravitational constant determined in laboratories and the constant determined from mine and bore-hole data. A differential Galileo experiment may be sensitive to such an effect.

Donald H. Eckhardt
Air Force Geophysics Laboratory
Hanscom AFB, Massachusetts 01731

Received 5 May 1986
PACS numbers: 04.90.+e

Fischbach et al. Respond: Since the publication of our reanalysis of the experiment of Eötvös, Pekár, and Fekete (EPF), considerable attention has been devoted to the question of what the actual source of the Eötvös anomaly is. The answer to this question is important not only in the design of experiments to check the EPF results, but also in establishing a theoretical connection between the EPF experiment and other systems which are sensitive to the putative "fifth force." These include the geophysical data and the K⁰-EPR system (see Ref. 1), where anomalies have been reported, as well as the satellite data from which interesting limits can be inferred.

The heart of the EPF apparatus consists of two dissimilar test masses attached to a bar, which is itself suspended from a torsion fiber. A force (such as the fifth force) which affects the test masses differently can cause a torque about the axis of the fiber, which is what EPF look for. However, even if the fifth force existed, its presence could go undetected if it were directed along the fiber axis. Since the fiber axis is determined by the local acceleration field \( \mathbf{g}_0 = \mathbf{a}_c + \mathbf{g}_N \), where \( \mathbf{a}_c \) is the centrifugal acceleration due to the Earth’s rotation, and \( \mathbf{g}_N \) is the Newtonian gravitational contribution due to the Earth, it follows that the fifth force can be detected in the EPF experiment only if the acceleration field \( \mathbf{y} \) that it produces is not parallel to \( \mathbf{g}_0 \). The following examples illustrate the implications of this observation.

1. Suppose, following Ref. 1, that the Earth is pictured as a uniform rotating sphere, and that \( \mathbf{y} \) arises from a force whose nominal range is 200 m. In this case \( \mathbf{y} \) is parallel to \( \mathbf{g}_N \), but \( \mathbf{y} \) and \( \mathbf{g}_0 \) are not parallel since \( \mathbf{a}_c \neq \mathbf{0} \). However, the angle \( \beta \) between \( \mathbf{y} \) and \( \mathbf{g}_0 \) is very small, \( \beta \approx \tan \beta = \mathbf{a}_c \sin \theta / g_0 \approx 1/581 \), where \( \theta \approx 45^\circ \) is the latitude where the EPF experiment took place.

2. Assuming the same picture for the Earth, let us add in the effects of local matter anomalies such as buildings (and their basements) and mountains. For these contributions \( \mathbf{y} \) is nearly horizontal, so that \( \mathbf{y} \) produces a relatively large torque about the fiber axis. This observation, which has been made previously by us \(^2,3\) and others, \(^4\) indicated the advantages of carrying out EPF-type experiments near mountains, and also demonstrated \(^2,3\) the importance of the building (and basement) where the EPF experiment took place. If we examine Eq. (1) of Ref. 3 we see that if the strength and range of the fifth force are as suggested by the geophysical data, then the effects of the building (and particularly its basement) are much larger than that of the Earth as a whole, even though the Earth is the main source of the gravitational force.

3. We next consider the effects of a nonspherical Earth by assuming that the Earth elastically deforms so that its surface lies along an equipotential of \( \mathbf{g}_0 \). As we noted in Ref. 2, this is a good assumption since the deviation of \( \mathbf{g}_0 \) from vertical is only 70′ even in the vicinity of Mt. Everest. (A similar point was made previously by Bizzeti \(^5\) and is the content of the accompanying Comment by Eckhardt.) \(^5\) Since \( \mathbf{y} \) is determined by the matter within a hemisphere of radius \( r \approx 200 \) m, \( \mathbf{y} \) will be locally perpendicular to the Earth’s surface, and if this surface is also an equipotential of \( \mathbf{g}_0 \), \( \mathbf{y} \) and \( \mathbf{g}_0 \) will be strictly parallel. Under these circumstances the Earth as a whole makes no contribution whatever to the EPF anomaly, as Eckhardt has also noted. However, this observation has limited practical significance, since we have already demonstrated in Refs. 2 and 3 that if the force is of short range then the dominant contributions in the EPF experiment will come from local departures from the Earth’s geoid.

(4) Finally we can consider the same situation as in (3) above, but under the assumption that \( \mathbf{y} \) arises from a force whose range is comparable to (or larger than) \( R_\mathbf{g} \). In this case \( \mathbf{y} \) is parallel to \( \mathbf{g}_N \), as in (1), and the angle between \( \mathbf{y} \) and \( \mathbf{g}_0 \) will again be of order \( \beta \). Here local departures from the geoid are no longer important, since the whole Earth contributes to both \( \mathbf{y} \) and \( \mathbf{g}_N \), and the EPF anomaly depends on the circumstance that \( \mathbf{a}_c = \mathbf{0} \). This was the picture that EPF had in mind in the design of their experiment.

This work was supported in part by the U.S. Department of Energy.

Ephraim Fischbach and Carrick Talmadge

Physics Department
Purdue University
West Lafayette, Indiana 47907

S. H. Aronson
Physics Department
Brookhaven National Laboratory
Upton, New York 11973

Received 28 October 1986
PACS numbers: 04.90.+e