Chapter 7
The Rise and Fall of the Fifth Force

Allan Franklin

On January 8, 1986, a headline in the *New York Times* announced, “Hints of Fifth Force[1] in Nature Challenge Galileo’s Findings.”[2] Four years later at the January 1990 Moriond Workshop,[3] Orrin Fackler, one of the experimenters working on the Fifth Force, stated, “The Fifth Force is dead.” The workshop was attended by representatives of virtually every group then working on the Fifth Force. No one disagreed.

In this essay I will outline the short, happy life of the Fifth Force, a proposed modification of Newton’s law of universal gravitation, involving both the composition dependence and the distance dependence of the force, from its origins to its demise.[4] The story begins with two seemingly independent strands: 1) K-meson decay and CP violation and 2) modifications of Newtonian gravity. When these two strands came together, the Fifth Force was born.

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[1] Physicists, at the time, spoke of four forces: 1) the strong or nuclear force, which holds the atomic nucleus together; 2) the electromagnetic force, which holds the atom together; 3) the weak force responsible for radioactive decay; and 4) gravity. Although the Fifth Force was a proposed modification of gravity, it involved the exchange of a different particle, a massive scalar particle, and so was considered as another force.

[2] This was a reference to the fact that the proposed Fifth Force, unlike gravity, was composition dependent. The Fifth Force between two lead masses would be different than the Fifth Force between a lead mass and a copper mass. The Fifth Force, as discussed below, also differed from the force of gravity in its dependence on the distance between the masses.

[3] The Moriond Workshops, devoted to“new and exotic phenomena,” were very important in the history of the Fifth Force. Not only were new results presented, but there was rigorous criticism of the new work, both formal and informal.

[4] For a more complete and detailed history, see Franklin (1993).

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7.1 The Rise . . .

7.1.1 K-Meson Decay and CP Violation

The history of the Fifth Force begins with a seeming digression because it involved not a modification of gravitational theory but rather an experimental test of and confirmation of that theory. In 1975 Colella et al. (1975) measured the quantum mechanical phase difference between two neutron beams caused by a gravitational field. Although this experiment showed the effects of gravity at the quantum level, it did not distinguish between general relativity and its competitors. This was because the experiment was performed at low speeds, where, as Ephraim Fischbach pointed out, all existing gravitational theories predicted the same results (Fischbach and Freeman 1979; Fischbach 1980). In this work Fischbach also considered whether gravitational effects might explain the previously observed violation of CP symmetry (combined particle-antiparticle and parity or space-reflection symmetry) in K_L^0 decays.[5] Fischbach pointed out that there were both experimental and theoretical arguments against gravity as the source of CP violation but wondered whether they were relevant to his work.

Theorists had already noted that for a long-range field that coupled differently to the K^0 and anti-K^0 mesons, a hyperphoton, and CP-violating effects would be proportional to the square of the K_L^0 energy (Bell and Perring 1964; Bernstein et al. 1964).[6] Weinberg (1964) had also shown that because neither strangeness nor isotopic spin, the supposed sources of the field, was conserved, the K^0 mesons, as well as all strange particles, would be totally unstable if the range of the force was the size of our galaxy.[7] (The ratio ($K_S^0 \rightarrow 2\pi$ + hyperphoton/$K_S^0 \rightarrow 2\pi$) would be approximately 10^{19}). These issues became moot when experiments showed that CP violation was constant as a function of energy (Galbraith et al. 1965; DeBouard et al. 1965).

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[5] CP symmetry allows the K_S^0 meson, the short-lived neutral K meson, but not the K_L^0 meson, its long-lived counterpart, to decay into two pions. In 1964 Fitch and Cronin and their collaborators (Christenson et al. 1964) found evidence for the two-pion decay for the K_L^0 meson and thus for CP violation.

[6] The K mesons, along with the Λ hyperon, had rather peculiar properties. They were copiously produced in strong interactions but decayed rather slowly by means of the weak interaction. No other particles, at the time, behaved in this manner. This led Gell-Mann and Nishijima to suggest that the K mesons possessed a property called strangeness, which was conserved in the strong, but not in the weak, interactions. This would explain the odd properties of the K mesons. The K^0 and its antiparticle the anti-K^0 had strangeness 1 and -1, respectively. At the time of the Fifth Force, the conservation of strangeness was an established conservation law. When physicists spoke of the strong interactions, they spoke of the K^0 the anti-K^0 mesons. In discussing the weak interaction, they spoke of the K_S^0 and K_L^0 mesons, which were different linear combinations of the K^0 the anti-K^0 mesons.

[7] The K^0 mesons would be stable if the range of the force was of the order of the radius of the Earth, something Weinberg regarded as unlikely.

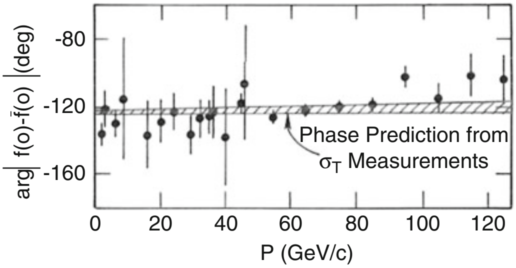

Fig. 7.1 The phase of the regeneration amplitude as a function of momentum. From Bock et al. (1979)

Fischbach was also encouraged by what he regarded as a "remarkable numerical relation." Using his calculated energy scale for the gravitational effect, gh/c, Δm, the known $K_L^0 - K_S^0$ mass difference, and an enhancement factor of $m_K/\Delta m$, for which no justification was given, he found that the gravitational effect in CP violation was 0.844×10^{-3}, whereas the CP-violating parameter $1/2\mathrm{Re}(\epsilon)$ was approximately equal to 0.82×10^{-3}. This seems indeed to be a remarkable coincidence because there is no known connection between gravity and CP violation. It is made even more remarkable when one realizes that the enhancement factor $m_K/\Delta m = 1.4 \times 10^{14}$.

A relativistic version of the experiment of Colella and colleagues did not seem feasible, so Fischbach began, in collaboration with Sam Aronson, an experimenter with considerable experience on K-meson experiments, to investigate whether such an experiment would be possible with K mesons. At this time, in the early 1980s, Aronson and his collaborators had been investigating the regeneration of K_S^0 mesons and found what seemed to be an energy dependence of the phase of the regeneration amplitude.[8] Although the results were consistent with a constant phase, the low-energy points have a larger phase then the high-energy points (Figure 7.1). Further investigation by Aronson, Fischbach, and their collaborators (Aronson et al. 1983a,b) revealed several suggestive energy dependences in the CP-violating parameters. Figure 7.2 shows the most significant effect. They concluded that, "The experimental results quoted in this paper are of limited statistical significance. *The evidence of a positive effect in the energy dependencies of* (the parameters) *is extremely tantalizing, but not conclusive*" (Aronson et al. 1983a, p. 488).[9] The experimenters concluded, "It is clear, however, that if the data...are correct, then the source of these effects will represent a new and hitherto unexplored realm of physics" (Aronson et al. 1983b, p. 516). An unkind referee remarked,"This latter statement also applies to spoon bending."[10] The paper was, however, published.

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[8] The phenomenon of regeneration was one of the very unusual properties of the K^0 mesons. An accelerator-produced beam of K^0 mesons contains $50\% K_S^0$ mesons and $50\% K_L^0$ mesons. If one waited until all of the K_S^0 mesons decayed and then allowed the remaining K_L^0 mesons to interact with matter, one found that the beam once again contained K_S^0 mesons. They had been regenerated.

[9] These energy dependences later disappeared, but at the time, they were "tantalizing" effects.

[10] Ephraim Fischbach gave me a copy of the referee's report.

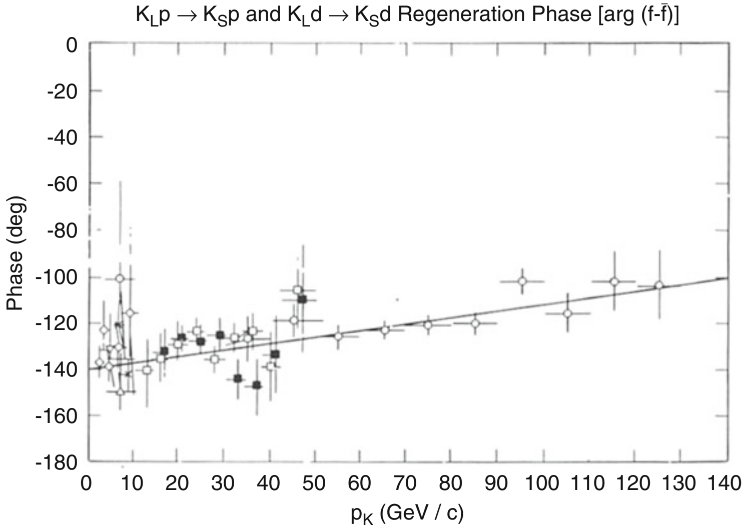

Fig. 7.2 The phase of the CP-violating amplitude as a function of momentum. From Aronson et al. (1983a).

7.1.2 Modifications of Newtonian Gravity

The second strand of our story involved proposed modifications of Newtonian gravity. Newtonian gravity and its successor, Einstein's general theory of relativity, although strongly supported by existing experimental evidence,[11] have not been without competitors. Thus, Brans and Dicke (1961) had offered a scalar-tensor alternative to general relativity. The theory contained a parameter ω, which for large values made the theory indistinguishable from general relativity. At this time ω had been found to be greater than 500, making the two theories indistinguishable.

In the early 1970s, Fujii (1971, 1972, 1974) suggested a modification of the Brans-Dicke theory that required a new, and hitherto unobserved, massive, scalar, exchange particle, in addition to the massless scalar and tensor particles of the Brans-Dicke theory. He found that including such a particle gave rise to an additional short-range force, of the order of 10 m–30 km, depending on details of the model. In Fujii's theory the gravitational potential took the form $V = -GmM/r[1 + \alpha e^{-r/\lambda}]$, where α was the strength of the new interaction and λ was its range. The first term was the ordinary gravitational potential. The second term was Fujii's modification. Fujii's model also predicted a gravitational constant

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[11] For an excellent and accessible discussion of this, see Will (1984). For more technical details, see Will (1981).

that varied with distance[12] and that the gravitational constant at large distances, G_∞, would be equal to $3/4G_{\mathrm{LAB}}$, the value at short distances.

Fujii also searched for possible experimental tests of his theory. Most interestingly for our story, he discussed the famous experimental test of Einstein's equivalence principle that had been performed by Roland von Eötvös and his collaborators in the early twentieth century and published in 1922 (Eötvös et al. 1922; this experiment, which is crucial to our history, is discussed below). Fujii noted that his new force predicted an effect that was smaller than the upper limit of five parts in 10^9 set by Eötvös, whose experiment was sensitive to such a short-range force. Fujii suggested redoing the Eötvös experiment and also other suggested possible geophysics experiments. He remarked that, although his calculated effect was, in fact, smaller than the limit Eötvös had set, local mass inhomogeneities would pose difficulties. As we shall see, this was a prescient comment.

Long (1974) investigated whether Newtonian gravity was valid at laboratory distances and found a small effect.[13] Long's work led Mikkelsen and Newman (1977) to examine the status of G, the gravitational constant. They concluded, "Constraints on G in the intermediate distance range from $10\,\mathrm{m} < r < 1\,\mathrm{km}$ are so poor that one cannot rule out the possibility that $G_c[G_\infty]$ differs greatly from $G_0[G_{\mathrm{LAB}}]$" (Mikkelsen and Newman 1977, p. 919). They pointed out that their analysis "does not even rule out Fujii's suggested value $G_c/G_0 = 0.75$" (Mikkelsen and Newman 1977, p. 924).

The most important summary of work on G, from the point of view of the subsequent history of the Fifth Force, was that given by Gibbons and Whiting (1981). Their survey included measurements of gravity in mineshafts and in submarines. The results for G from those measurements were slightly higher than those obtained in the laboratory, but because of experimental uncertainties, no firm conclusion could be drawn. Gibbons and Whiting summarized the situation as follows. "It has been argued that our experimental knowledge of gravitational forces between 1 m and 10 km is so poor that it allows a considerable difference between the laboratory measured gravitational constant and its value on astronomical scales, an effect predicted in theories of the type alluded to above [these included Fujii's theory]" (Gibbons and Whiting 1981, p. 636). Although experiment allowed for such a difference between the laboratory and astronomical values of G, there were reasonably stringent limits on any proposed modification in the distance range 1–10 km. There was, however, a small window of opportunity for a force with a strength approximately one percent that of gravity and with a range between 1 meter and 1 kilometer (Figure 7.3).

At this time there were also hints that the value of G measured in the laboratory differed from that found in geophysics experiments, although experimental uncertainties precluded a definite conclusion (Stacey and Tuck 1981; Stacey et al. 1981).

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[12] Although a varying constant seems like an oxymoron, it is useful shorthand.

[13] Later work would show that no effect existed.

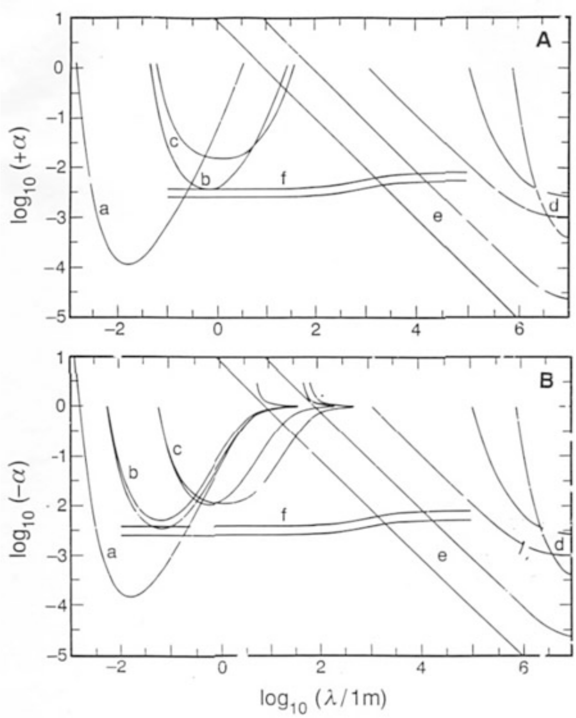

Fig. 7.3 $\log_{10}\alpha$ vs $\log_{10}(\lambda/1m)$. α, the strength of the Fifth Force, is constrained to lie below the curves. λ is the range of the force. From Gibbons and Whiting (1981).

7.1.3 *The Fifth Force*

Until early 1983 the two strands, that of the energy dependence of the CP-violating parameters in K-meson decay and that of modifications of Newtonian gravity and their experimental tests, proceeded independently. At about this time, Fischbach became aware of the discrepancies between the laboratory and geophysical measurements of G and the anomalies for gravitational theory. He made no connection between the two problems because he was still thinking in terms of a long-range force, which had been experimentally ruled out for CP violation. In early 1984 he realized that this would not apply to a short-range force and that the effect could be much smaller. At this time he also became aware of the summary by Gibbons and Whiting, which did not rule out such a force. He realized that a short-range force might be a common solution to both problems.

Fischbach, Aronson, and their collaborators looked for other places in which such an effect might be seen with existing experimental sensitivity. They found only three:

1) the K^0-meson system at high energy, which they had already examined;
2) the comparison between satellite and terrestrial determinations of g, the local gravitational acceleration;

3) the original Eötvös experiment, which had measured the difference between the gravitational and inertial masses of different substances, and a set of an upper limit of five parts in 10^9 for that difference. If there were a short-range, composition-dependent force, then it might show up in this experiment.

The apparent energy dependence of the CP-violating parameters along with the discrepancy between gravitational theory and the mineshaft experiments led Fischbach and his colleagues to reexamine the original data of Eötvös et al. (1922) to see if there was any evidence for a short-range, composition-dependent force. By this time they knew of Holding's and Tuck's result which gave G measured in a mine as $G = (6.730 \pm 0.003) \times 10^{-11}\ \text{m}^3\ \text{kg}^{-1}\ \text{s}^{-2}$ in disagreement with the best laboratory value of $(6.6726 \pm 0.0005) \times 10^{-11}\ \text{m}^3\ \text{kg}^{-1}\ \text{s}^{-2}$. This result was, however, still uncertain because of possible regional gravity anomalies. Fischbach and colleagues used a modified gravitational potential $V = -GmM/r[1+\alpha e^{-r/\lambda}]$, which they remarked could explain the geophysical data if $\alpha = (-7.2 \pm 3.6) \times 10^{-3}$ and $\lambda = 200 \pm 50\,\text{m}$. This was from a private communication from Stacey. Details appeared later in Holding et al. (1986). This result was within the window found by Gibbons and Whiting. This potential had the same mathematical form as that suggested much earlier by Fujii. Recall that Fujii had also suggested redoing the Eötvös experiment.[14]

The apparatus for the Eötvös experiment is shown schematically in Figure 7.4. One can see that because of the rotation of the Earth, the gravitational force is not parallel to the fiber. If the gravitational force on one of the masses differs from

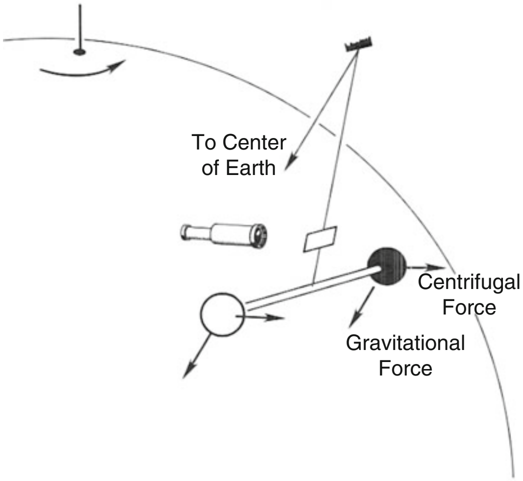

Fig. 7.4 A schematic view of the Eötvös experiment. From Will (1984).

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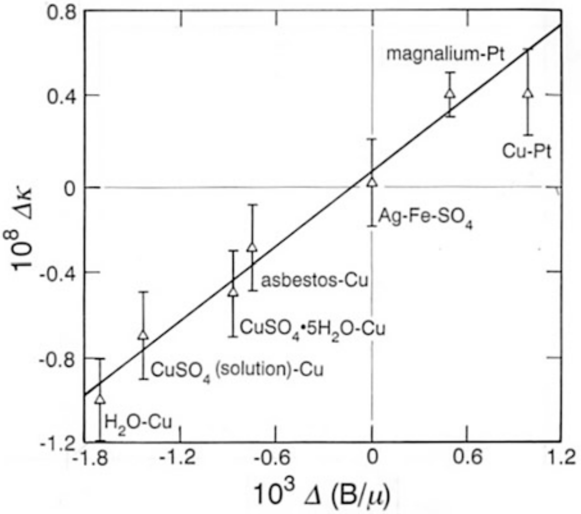
[14] Fischbach has stated that Fujii's work had no direct influence on this work. He keeps detailed chronological notes of papers read. He reports that he has notes on Fujii's work at this time, but does not recall it having any influence on his work.

Fig. 7.5 $\Delta\kappa$, as a function of $\Delta(B/\mu)$. From Fischbach et al. (1986b).



that on the other mass or if the ratio of the gravitational to inertial mass of the two objects differs, then the rod will rotate about the fiber axis. Fischbach and colleagues attempted to find a single explanation for the gravitational discrepancies and the apparent energy dependence of the CP-violating parameters. They found that if they considered a hypercharge field with a small, finite mass hyperphoton (the K^0 and anti-K^0 have opposite hypercharges), they obtained a potential of the same mathematical form as shown above. They also found that $\Delta\kappa = \Delta a/g$, the fractional difference in gravitational acceleration for two substances, was proportional to $\Delta(B/\mu)$ for the two substances, where B was the baryon number and μ was the mass of the substance in units of the mass of atomic hydrogen.

Their reanalysis of the Eötvös data is shown in Figure 7.5 (Fischbach et al. 1986a).[15] The clear linear dependence seen, showing a composition dependence, is supported by a least-squares fit to the equation $\Delta\kappa = a\Delta(B/\mu) + b$. They found $a = (5.65 \pm 0.71) \times 10^{-6}$ and $b = (4.83 \pm 6.44) \times 10^{-10}$. This is an eight-standard deviation difference from the zero expected from Newtonian gravity or general relativity, which are both composition independent. They concluded, "We find that the Eötvös-Pekar-Fekete data are sensitive to the composition of the material used,

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[15] An interesting aspect of this reanalysis was reported in a footnote to this paper. Rather than reporting the observed values of $\Delta\kappa$ for the different substances directly, Eötvös and his colleagues had presented their results relative to platinum as a standard."The effect of this combining say $\Delta\kappa(H_2O - Cu)$ and $\Delta\kappa(Cu - Pt)$ to infer $\Delta\kappa(H_2O - Pt)$ is to reduce the observed effect (for water and platinum) from 5σ to 2σ" (Fischbach et al. 1986a). $\Delta\kappa(H_2O - Cu) = (-10 \pm 2) \times 10^{-9}$ and $\Delta\kappa(Cu - Pt) = (+4 \pm 2) \times 10^{-9}$, respectively. Adding them to obtain $\Delta\kappa(H_2O - Pt)$ yields $(-6 \pm 3) \times 10^{-9}$. Fischbach and colleagues chose to use copper as their standard which minimized the need for such additions.

and that their results support the existence of an intermediate-range coupling to baryon number or hypercharge" (Fischbach et al. 1986a, p. 3).[16] They calculated the coupling constant for their new interaction for both the Eötvös data and for the geophysical data and found that they differed by a factor of 15, which they found "surprisingly good" in view of the simple model of the Earth they had assumed. As discussed below, not everyone was so sanguine about this.

It seems fair to summarize the paper of Fischbach and his colleagues as follows. A reanalysis of the original Eötvös paper presented a suggestive evidence for an intermediate-range, composition-dependent force. With a suitable choice of parameters (a force about one percent of the gravitational force with a range of approximately 100 meters), they could relate this force to measurements of gravity in mineshafts and to a suggested energy dependence in the parameters of the neutral K-meson system.

7.2 . . . and Fall

7.2.1 *The Immediate Reaction*

The suggestion by Fischbach and his colleagues had an immediate impact in the popular press. On January 8, 1986, only 2 days after the publication of their paper, a headline in the *New York Times* announced, "Hints of Fifth Force in Nature Challenge Galileo's Findings." This referred to the composition dependence of the suggested force, which implied that different substances would fall at different rates. This would disagree with what Galileo was supposed to have observed at the Leaning Tower of Pisa.[17] This was the naming of the "Fifth Force." On January 15 an editorial in the *Los Angeles Times* also discussed the subject. It cited the skepticism of Richard Feynman, a Nobel Prize winner in physics. Feynman's skepticism concerned the factor of 15 difference (a more careful analysis gave a factor of 30) between the force needed to explain the Eötvös data and that needed to explain the gravitational mine data. Feynman argued that the geophysical results already showed that the hypothesis was incorrect.

The battle would not, however, be conducted or decided in the popular press but rather in the technical literature. One of the most important early developments was the recognition that local mass asymmetries, such as cliffs, hills, or large buildings, were of crucial importance not only in the reanalysis of the Eötvös experiment but

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[16] A skeptic might remark that the effect is seen only when the data are plotted as a function of $\Delta(B/\mu)$, a theoretically suggested quantity. As Alvaro De Rujula remarked,"In that case, Eötvös and collaborators would have carried their secret to their graves: how to gather ponderous evidence from something like baryon number decades before the neutron was discovered" (De Rujula 1986a, p. 761). Although one may be surprised, along with De Rujula, that data taken for one purpose takes on new significance in the light of later experimental and theoretical work, it is not unprecedented.

[17] There is some question as to whether Galileo ever performed this experiment. See Cooper (1935).

also in the design of experiments to search for the Fifth Force. Thodberg (1986) pointed out that the Eötvös reanalysis required an attractive Fifth Force, whereas the geophysical results required a repulsive Fifth Force. Fischbach and colleagues remarked that Thodberg was indeed correct but that further analysis had shown "that one cannot in fact deduce from the EPF [Eötvös-Pekar-Fekete] 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" (Fischbach et al. 1986b, p. 2464). In order to determine the magnitude and sign of the effect, one needed more detailed knowledge of the local mass distribution than was then available. Fischbach and his collaborators even searched for a detailed map of the University of Budapest campus, where Eötvös had done his work They also tried to discover whether the building in which the experiment was done had a basement, which would influence the local mass distribution. The importance of the local mass distribution could also explain the numerical discrepancy between the force derived from the Eötvös reanalysis and that found from the mine data that had bothered Feynman and others.

Other authors suggested redoing the Eötvös experiment by placing the torsion balance on a high cliff or in a tunnel in such a cliff (Bizzeti 1986; Milgrom 1986; Neufeld 1986; Thieberger 1986; De Rujula 1986a,b). They claimed that such a location, which had a large local mass asymmetry, could increase the sensitivity of the experiment by a factor of 500. De Rujula (1986a) and Eckhardt (1986) argued that the original Eötvös reanalysis would not have been at all sensitive to a Fifth Force without local mass inhomogeneities. They noted that for a deformed rotating Earth, the fiber is perpendicular to the deformed surface. For a homogeneous Earth, the symmetry of the local matter distribution will give no net force on the balance. De Rujula quipped, "Although malicious rumor has it that Eötvös himself weighed more than 300 pounds [suggesting that Eötvös himself was the source of a local mass asymmetry], unspecific hypotheses are not, a priori, particularly appealing" (De Rujula 1986a, p. 741). De Rujula's quip is completely without merit. Eötvös was a mountain climber, and photographs indicate rather clearly that he did not weigh 300 pounds. In fact, a peak in the Dolomites is named for him.

The initial reanalysis of the Eötvös experiment was incorrect because it did not consider local mass asymmetries. The subsequent criticism not only modified the theoretical model but also allowed one to design experiments that would be far more sensitive to the presence of the hypothesized Fifth Force. Other critics suggested that there was, in fact, no observed effect and that Fischbach and his colleagues had made an error in the reanalysis. De Rujula, however, performed his own reanalysis of the Eötvös data and obtained results identical to those of Fischbach and collaborators.[18]

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[18] De Rujula's analysis was important because it answered the question of whether one should use reduced mass. In several measurements Eötvös used a brass vial to hold the sample of the material. In reporting the final results, he multiplied the measured value $\Delta\kappa$ by a factor $(M_{Sample} + M_{Container})/M_{Sample}$. This assumed that the container had no effect on the measurement. This was a reasonable procedure if one was interested only in setting an upper limit but might overestimate

Some physicists suggested that experiments on K mesons had already ruled out the Fifth Force. Questions were also raised as to whether one could explain the Eötvös results in terms of more conventional physics, without invoking a new force. (For details see Franklin 1993.)

Although the criticism may have made the reanalysis of the Eötvös data somewhat uncertain, it did not prevent physicists from planning new, more sensitive versions of old experiments and designing new ones to test for the presence of the Fifth Force. At the same time, theoretical physicists were attempting to find an explanation for the force and to see if it had implications in other areas. Unfortunately in all of these theoretical studies, the expected effects were quite small and did not suggest new experimental tests.

At the end of 1986, the evidential context for the Fifth Force was much the same as it had been on January 6, 1986, when Fischbach and colleagues had first published it. By early 1986 the inverse-square law of gravity had been tested at very short distances and had been confirmed, but the possibility of an intermediate-range force remained. Doubts had been raised about the proposed mechanism of the force, but other explanations were possible. The tantalizing effects of the reanalysis of the Eötvös experiment, the K-meson parameters, and the measurements of gravity in mineshafts still remained.

The attitude of scientists toward the Fifth Force at this time varied from outright rejection to regarding it as highly suggestive and plausible. Sheldon Glashow, a Nobel Prize-winning theoretical physicist, was quite negative. "Unconvincing and unconfirmed kaon data, a reanalysis of the Eötvös experiment depending on the contents of the Baron's wine cellar [an allusion to the importance of local mass inhomogeneities], and a two-standard-deviation geophysical anomaly! Fischbach and his friends offer a silk purse made out of three sows ears, and I'll not buy it" (quoted in Schwarzschild (1986, p. 20)). John Maddox noted that, "Fischbach et al. have provided an incentive for the design of better measurements by showing what kind of irregularity it will be sensible to look for" (1986, p. 173). An important feature of experimental design is knowing how large the observed effect is supposed to be. A much more positive view was, "Considerable, and justified, excitement has been provoked by the recent announcement–that a reanalysis of the Eötvös experiment together with recent geophysical gravitational measurements supports the existence of a new fundamental interaction" (Lusignoli and Pugliese 1986, p. 468).

It seems clear, judging by the substantial amount of work published in 1986, that a significant segment of the physics community thought the Fifth Force hypothesis was plausible enough to be worthy of further investigation. Although almost invisible in the published literature, experiments were being designed, performed, and analyzed. The results would start to appear in early 1987.

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the effect. Fischbach and collaborators had used the"composite" value, whereas De Rujula used the reduced value (vials not included). The agreement of the two slopes showed that the analysis was independent of which one used, as long as one remained consistent.

7.2.2 A Composition-Dependent Force? Was Galileo Wrong?

There would be two sets of discordant experimental results that had to be resolved in order to decide whether there was a Fifth Force. The first strand of experimental investigation of the Fifth Force was the search for a composition dependence of the gravitational force. (The second involved the question of a proposed deviation from Newton's inverse-square law of gravity and is discussed below.) The former were the first published experimental results. Recall that the strongest piece of evidence cited when the Fifth Force was initially proposed came from a reanalysis of the Eötvös experiment. That reanalysis had shown a large and surprising composition-dependent effect. This was the effect that was subsequently investigated. Both types of experiment are shown in Figure 7.6.

Two types of composition-dependence experiments are shown in the top row. In order to observe the effect of a short-range force such as the Fifth Force, one needs a local mass asymmetry. This asymmetry was provided by either a terrestrial source—a hillside or a cliff—or by a large, local, laboratory mass. If there were a composition-dependent, short-range force, the torsion pendulum made of two different substances would twist. A variant of this experiment was the float experiment, in which an object floated in a fluid and in which the difference in gravitational force on the float and on the fluid would be detected by the motion of the float. These were done with terrestrial sources.

The results of the first tests for a composition-dependent force appeared in January, 1987, 1 year after the Fifth Force first appeared in print. They disagreed. Peter Thieberger, using a float experiment, found results consistent with the presence

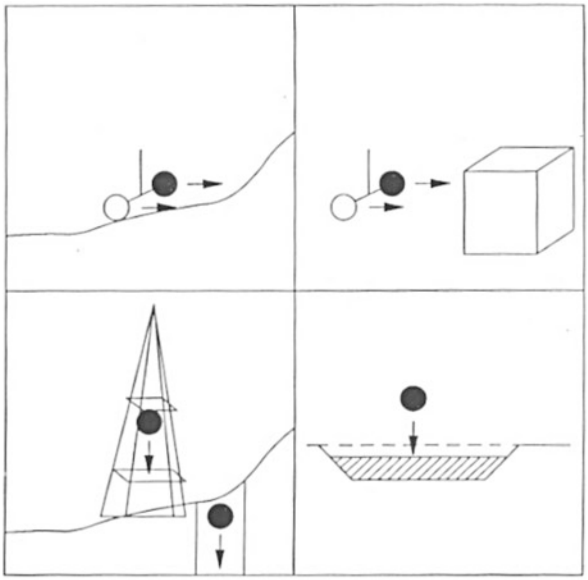

Fig. 7.6 Different types of experiment to measure the Fifth Force. The upper row shows composition-dependence experiments. The bottom row shows distance-dependence experiments. The left column shows terrestrial sources; the right column shows laboratory/controlled sources. From Stubbs (1990).

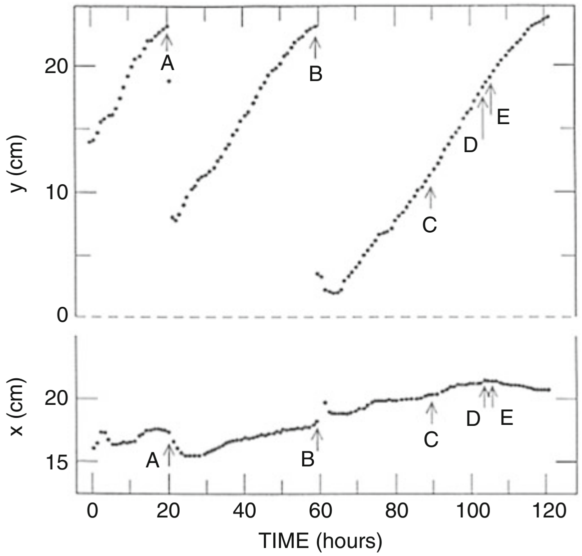

Fig. 7.7 The position of the center of the copper sphere as a function of time. The y axis points away from the cliff. The position of the sphere was reset at points A and B. From Thieberger (1987).

of such a force (Thieberger 1987). A group at the University of Washington, headed by Eric Adelberger and whimsically named the Eöt-Wash group, found no evidence for such a force and set rather stringent limits on its presence (Adelberger et al. 1987).

The results of Thieberger's experiment, performed on the Palisades cliff in New Jersey, are shown in Figure 7.7. Thieberger measured the difference in force on the copper float and on the water. One can see that the float moves quite consistently and steadily away from the cliff (the y-direction) as one would expect if there were a Fifth Force. (One wag remarked that all the experiment showed was that any sensible float wanted to leave New Jersey.) Thieberger eliminated other possible causes for the observed motions. These included the possible effects of magnetic forces, thermal gradients, and leveling errors. No significant effects were observed. He also rotated his apparatus by 90° to check for possible instrumental asymmetries and obtained the same positive result. In addition, he performed the same experiment at another location, one without a local mass asymmetry or cliff, and found no effect, as expected. He concluded, "The present results are compatible with the existence of a medium-range, substance-dependent force which is more repulsive (or less attractive) for Cu than for H_2O .... Much work remains before the existence of a new substance-dependent force is conclusively demonstrated and its properties fully characterized" Thieberger (1987, p. 1068).

The Eöt-Wash experiment used a torsion pendulum located on the side of a hill on the University of Washington campus. If the hill attracted the copper and beryllium test bodies, used in the apparatus, differently, then the torsion balance would experience a net torque. None was observed (Figure 7.8). The group also eliminated other possible causes of effects that might either mimic the presence of a

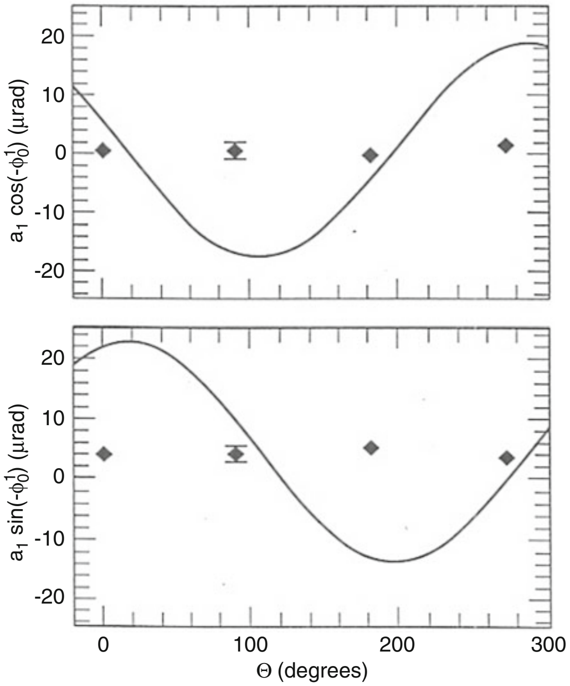

Fig. 7.8 Deflection signal as a function of Θ. The theoretical curves correspond to a Fifth Force with a strength $\alpha = 0.01$ and a range $\lambda = 100\,m$. From Raab (1987) .

Fifth Force or mask the effects of such a force. The possible effects of electrostatic forces, instrumental asymmetries, magnetic forces, gravity gradients, and the tilt of the apparatus were measured and shown to be negligible.

The discordant results were an obvious problem for the physics community. Both experiments appeared to have been carefully done, with all plausible and significant sources of possible error and background adequately accounted for. Yet the two experiments disagreed. In this case we are dealing with attempts to observe and measure the same quantity, a composition-dependent force, with very different apparatuses, a float experiment, and a torsion pendulum. Was there some unknown but crucial background in one of the experiments that produced the wrong result? To this day, no one has found an error in Thieberger's experiment, but the consensus is that the Eöt-Wash group is correct and that Thieberger is wrong—that there is no Fifth Force. How was the discord resolved?

In this episode it was resolved by an overwhelming preponderance of evidence. The torsion pendulum experiments were repeated by others including Fitch et al. (1988), Cowsik et al. (1988), Bennett (1989), Boynton (1990), Boynton et al. (1987), Boynton and Peters (1989),[19] and Newman (Newman et al. 1989; Nelson et al.

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[19] Boynton had initially found a 3.5 standard-deviation positive effect. His later, more accurate experiments found no effect.

1990), and by the Eöt-Wash group (Adelberger 1988, 1989; Heckel et al. 1989; Stubbs et al. 1989). None gave evidence for a Fifth Force.

Bennet's experiment is particularly interesting. He reported a measurement of the difference in force exerted on copper and lead masses by a known mass of water, located nearby. The experiment used a torsion balance located near the Little Goose Lock on the Snake River in eastern Washington, in which the water level was changed periodically to allow the passage of boats. This change in water level provided the known mass of water. The difficulty of real, as opposed to ideal, experiments is clearly illustrated in this experiment. "Because the data were taken during a dry period (August 1988), separate lock fillings could not be made just for the experiment. On average there were four lockages a day from barge traffic which could occur at any hour of the day or night with only a half-hour advance notice." The apparatus needed minor adjustment every 4 or 5 hours and then took about 2 hours to stabilize, allowing good data to be taken for the next 2 or 3 hours. "The success of a particular run depended on the coincidence of this observation period with the arrival of lock traffic and, typically only one could be observed in a period of about 6 *h* during weekdays. Fortunately, traffic on weekends was heavier because of pleasure craft. Although consistent with individual isolated experiments, by far the best data were obtained on Sunday, 21 August 1988, when an armada of small craft went up and down the river" (Bennett 1989, p. 367).

All of the repetitions, in different locations and with different substances, gave consistently negative results. There was also evidence against the Fifth Force from modern versions of Galileo's Leaning Tower of Pisa experiment performed by Kuroda and Mio (1989a,b, 1990) and by Faller and his collaborators (Niebauer et al. 1987; Speake et al. 1990). As more negative evidence was provided, the initial and startling effect claimed by Fischbach and collaborators became less and less dramatic (Figures 7.9 and 7.10). In fact, one might reasonably say that the effect had disappeared. In addition, Bizzeti, using a float apparatus similar to that used by

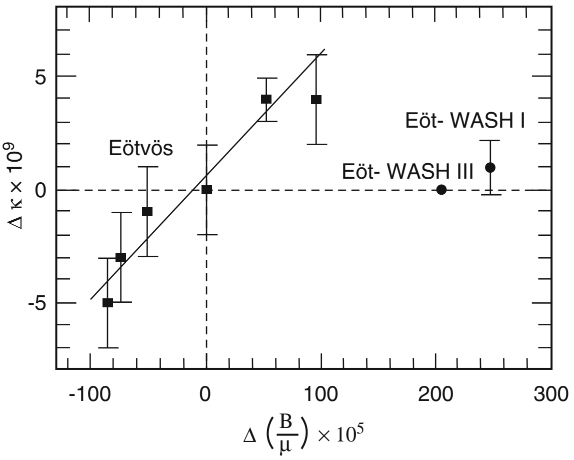

Fig. 7.9 Comparison of the Eötvös reanalysis of Fischbach et al. with the results of the Eöt-Wash I and III experiments. The error bar on the Eöt-Wash III datum is smaller than the dot. From Adelberger (1989).

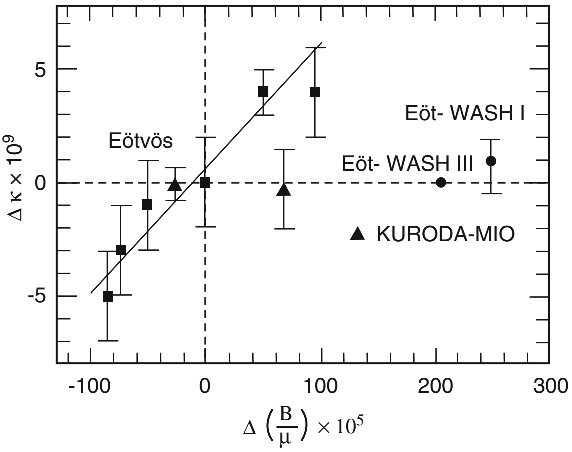

Fig. 7.10 The results of Kuroda and Mio added to Figure 7.9.

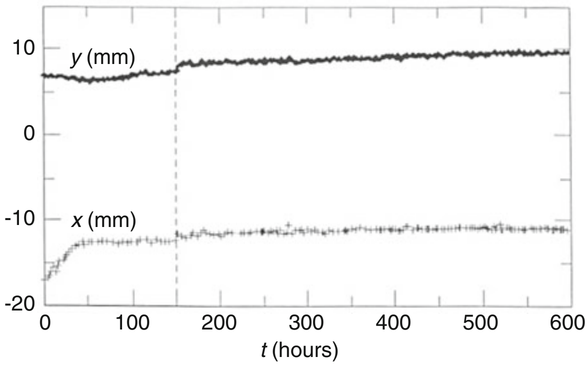

Fig. 7.11 The position of the sphere completely immersed in liquid as a function of time. The vertical line marks the time at which the restraining wires were removed. From Bizzeti et al. (1988).

Thieberger, also obtained results showing no evidence of a Fifth Force (Bizzeti et al. 1988, 1989a,b). (Compare Bizzeti's results (Figure 7.11) with those of Thieberger (Figure 7.7)). Bizzeti's result was quite important. Had he agreed with Thieberger, then one might well have wondered whether there was some systematic difference between torsion balance experiments and float experiments that gave rise to the conflicting results. This did not happen. There was an overwhelming preponderance of evidence against composition dependence of the Fifth Force. Even Thieberger, although he had not found any error in his own experiment, agreed. "Unanticipated spurious effects can easily appear when a new method is used for the first time to detect a weak signal…Even though the sites and the substances vary, effects of the magnitude expected [from his initial experiment] have not been observed.…It now seems likely that some other spurious effect may have caused the motion observed at the Palisades cliff" (Thieberger 1989, p. 810).

7.2.3 Towers and Mineshafts: The Distance Dependence of the Gravitational Force

A second way in which the presence of the Fifth Force could be tested was by investigating the distance dependence of the gravitational force, to see if there was a deviation from Newton's inverse-square law. This type of experiment measured the variation of gravity with position, usually in a tower, in a mineshaft, or in a borehole (Figure 7.6, bottom row). All of the experiments used a standard device, a LaCoste-Romberg gravimeter, to measure gravity. The measurements were then compared with the values calculated using a model of the Earth, surface gravity measurements, and Newton's law of gravitation. This type of calculation had been done often and was regarded as reliable. The results of the calculation were, however, quite sensitive to the surface gravity measurements and to the model of the Earth used. This made knowledge of the local mass distribution and of the local terrain very important.

Evidence from such measurements had provided some of the initial support for the existence of the Fifth Force. Geophysical measurements during the 1970s and 1980s had given values of G, the universal gravitational constant, that were consistently higher, by about 1%, than that obtained in the laboratory. Because of possible local mass anomalies, they were also "tantalizingly uncertain." After the proposal of the Fifth Force, further experimental work was done. At the Moriond Workshop in January, 1988, Donald Eckhardt presented results from the first of the new tower gravity experiments (Eckhardt et al. 1988, 1989). The results differed from the predictions of the inverse-square law by $-500 \pm 35\,\mu Gal$, ($1\,\mu Gal = 10^{-8}\,\mathrm{ms}^{-2}$) at the top of the tower (Figure 7.12).

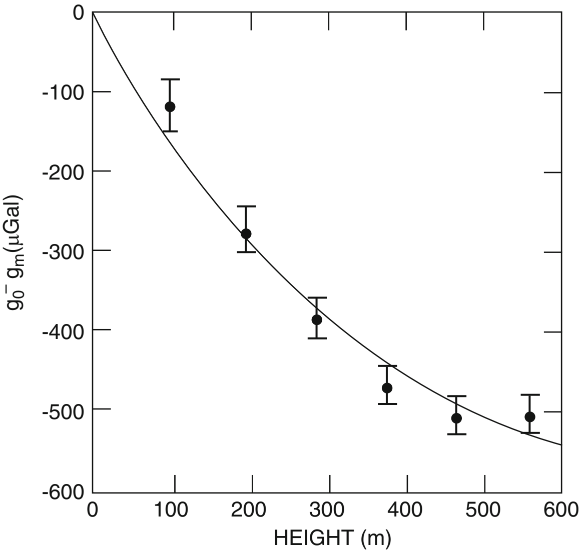

Fig. 7.12 Eckhardt's results for the difference between the measured and calculated values of g, the acceleration due to gravity, as a function of height. From Fairbank (1988).

Further evidence for the Fifth Force was provided by a group that measured the variations in gravity in a borehole in the Greenland ice cap (Ander et al. 1989). They found an unexplained 3.87 $mGal$ discrepancy between the measurements taken at a depth of 213 m and those taken at a depth of 1673 m. This was larger and opposite in sign to the geophysics results of Stacey and collaborators. The experimental advantage of the Greenland experiment was the uniform density of the ice cap. The disadvantages were the paucity of surface gravity measurements and, as the group noted, the presence of underground geological features that could produce gravitational anomalies.

The Livermore group, using measurements taken at the BREN Tower at the Nevada test site, found a 2.5% discrepancy between the observed gravity gradient and that predicted by a standard Newtonian model of the Earth (Thomas et al. 1988). This result disagreed in magnitude with Stacey's 0.52% discrepancy and, in both sign and magnitude, with Eckhardt's 0.29% discrepancy. They concluded, however, "that the model [of the Earth] does not reflect the total mass distribution of the Earth with sufficient accuracy to make a statement about Newtonian gravity [or about the Fifth Force]" (Thomas et al. 1988, p. 591). The evidence from tower and mineshaft experiments prior to 1988 was consistent with the Fifth Force, albeit with considerable uncertainty. There was, however considerable, although not unambiguous negative evidence from other types of experiment. Negative evidence from tower experiments would, however, be forthcoming, and it is the discrepancy between the tower results that I will address here.

Even before those negative results appeared, questions and doubts were raised concerning the positive results. It was not, in fact, the gravity measurements themselves that were questioned. These were all obtained with a standard and reliable instrument. It was, rather, the theoretical calculations used for the theory-experiment comparison that were criticized. One of the important features needed in these calculations was an adequate model of the Earth.

The Greenland group's calculation was the first to be criticized. It was subjected to severe criticism, particularly for the paucity of surface gravity measurements near the location of their experiment (their survey included only 16 such points) and for the inadequacy of their model of the Earth. It was pointed out that there were underground features in Greenland of the type that could produce such gravitational anomalies. The group later admitted that their result could be interpreted either as evidence for non-Newtonian gravity (a Fifth Force) or explained by local density variations. "We cannot unambiguously attribute it to a breakdown of Newtonian gravity because we have shown that it might be due to unexpected geological features below the ice" (Ander et al. 1989, p. 985).

Robert Parker, a member of the Greenland group, as well as David Bartlett and Wesley Tew, suggested that both the positive evidence for the Fifth Force of Eckhardt and collaborators and that from the mineshaft experiments could be explained by either local density variations or by inadequate modeling of the local terrain (Parker and Zumberge 1989; Bartlett and Tew 1989a).

Eckhardt disagreed. His group presented a revised, and lower, value for the deviation from Newtonian gravity at the top of their tower of 350 ± 110μGal

(Eckhardt et al. 1989). They attributed this change, a reduction of approximately one-third, to better surface gravity data and to finding a systematic elevation bias in their previous survey. (Gravity measurements tend to be made on roads rather than in ditches or surrounding fields. Roads are usually higher than their surroundings, giving rise to an elevation bias.) "We also had the help of critics who found our claims outrageous." They concluded that, "nevertheless the experiment and its reanalysis are incomplete and we are not prepared to offer a final result" (Eckhardt et al. 1989, p. 526).

The Lawrence Livermore Laboratory group presented a result from their gravity measurements at the BREN tower at the Nevada test site (Kasameyer et al. 1989). To overcome the difficulties with their previous calculations, they had extended their gravity survey to include 91 of their own gravity measurements within 2.5 km of the tower, supplemented with 60000 surface gravity measurements within 300 km, done by others. Contrast this with the 16 points in the Greenland survey. They presented preliminary results in agreement with Newtonian gravity, reporting that, at the top of the tower, there was no difference between the measured and predicted values.

Bartlett and Tew (1989b, 1990) continued their work on the effects of local terrain. They argued that the Hilton mine results of Stacey and his collaborators could also be due to a failure to include local terrain in their theoretical model. They communicated their concerns to Stacey privately. Their view was confirmed when, at the General Relativity and Gravitation Conference in July 1989, G. J. Tuck reported that their group had incorporated a new and more extensive surface gravity survey into their calculation. Preliminary analysis of these data indicated a regional bias that reduced the anomalous gravity gradient to two-thirds of the value that they had previously reported (with a 50% uncertainty). With such a large uncertainty, the results of Stacey and his collaborators could no longer be considered as support for the Fifth Force.

Parker and Mark Zumberge, two members of the Greenland group, offered a general criticism of tower experiments. They argued, in some detail, that they could explain the anomalies reported in both Eckhardt's tower experiment and in their own ice cap experiment, using conventional physics and plausible local density variations. They concluded that there was "no compelling evidence for non-Newtonian long-range forces in the three most widely cited geophysical experiments [those of Eckhardt, of Stacey, and their own]…and that the case for the failure of Newton's Law could not be established" (Parker and Zumberge 1989, p. 31).

The last hurrah for tower gravity experiments that supported the Fifth Force was signaled in the paper, "Tower Gravity Experiment: No Evidence for Non-Newtonian Gravity" (Jekeli et al. 1990). In this paper Eckhardt's group presented their final analysis of their data, which included a revised theoretical model, and concluded that there was, in fact, no deviation from Newtonian gravity. (See Figure 7.13, and contrast this with their initial positive result shown in Figure 7.12). Two subsequent tower results also supported Newton's Law.

The discord had been resolved. The tower and mineshaft measurements were correct. It was the comparison between theory and experiment that had led to the

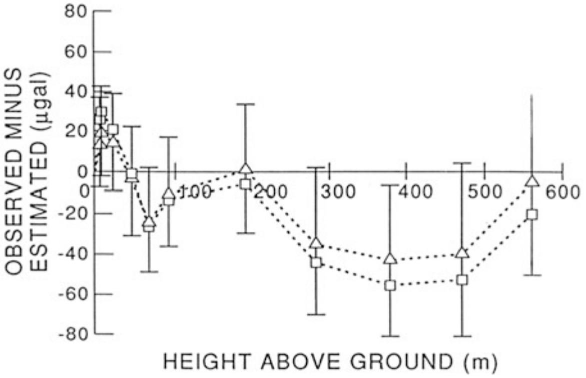

Fig. 7.13 Difference between measured and calculated values of *g* as a function of height. From Jekeli et al. (1990).

discord. It had been shown that the results supporting the Fifth Force could be explained by inadequate theoretical models, either failure to account adequately for local terrain or the failure to include plausible local density variations.

Scientists make decisions in an evidential context. The Fifth Force was a modification of Newtonian gravity. Newtonian gravity and its successor, general relativity, were strongly supported by other existing evidence. In addition, there were other credible negative tower gravity results that did not suffer from the same difficulties as did the positive results. There was also, as discussed earlier, an overwhelming preponderance of evidence against the Fifth Force from other types of experiment. The decision as to which theory-experiment comparison was correct was not made solely on the basis of the experiments and calculations themselves, although one could have justified this. Scientists examined all of the available evidence and came to a reasoned decision about which were the correct results—and concluded that the Fifth Force did not exist.

In both instances discussed in this paper, the composition dependence and the distance dependence of the proposed Fifth Force, the decision that such a force did not exist was made on the basis of reasons that allow us to consider experimental results as the basis for scientific knowledge. In the case of the distance dependence, it was shown that the positive results had overlooked effects in their theoretical calculations that resulted in an incorrect experiment-theory comparison. This, combined with credible negative results, argued against the existence of the Fifth Force. The discrepancy between the Thieberger and Adelberger results on the composition dependence of the Fifth Force was resolved by an overwhelming preponderance of evidence. In addition, Bizzeti and collaborators, using an apparatus quite similar to that of Thieberger, found no evidence for the Fifth Force. This argued against any crucial difference between the different types of apparatus being responsible for the discordant results.

In 1990, at a Moriond Workshop attended by most of those working in the field, Orrin Fackler of the Livermore group remarked, “The Fifth Force is dead.” No one disagreed. The Fifth Force is not with us.[20]

7.3 Epilogue: The Fifth Force Since 1991

We left our story at the 1990 Moriond Workshop with the stated demise of the Fifth Force. As even Ephraim Fischbach and Carrick Talmadge, two of the proposers of the initial hypothesis remarked, “No compelling evidence has yet emerged that would indicate the presence of a fifth force, ...” (Fischbach and Talmadge 1992, p. 214).

Despite these obituaries, work on the Fifth Force, both experimental and theoretical, has continued into the twenty-first century. This includes explicit tests of the hypothesis. Other works, on the universality of free fall, on possible violation of Newton’s inverse-square law of gravity and on the weak equivalence principle in general relativity also have relevance for the Fifth Force. These later papers, although relevant, do not always mention the Fifth Force explicitly or cite the initial paper of Fischbach and his collaborators. Thus, the Eöt-Wash collaboration stated,

> The universality of free fall (UFF) asserts that a point test body, shielded from all known interactions except gravity, has an acceleration that depends only on its location. The UFF is closely related to the gravitational equivalence principle, which requires an exact equality between gravitational mass m_g and inertial mass m_i and therefore the universality of gravitational acceleration. Experimental tests of the UFF have two aspects —they can be viewed as tests of the equivalence principle or as probes for new interactions that violate the UFF. (Su et al. 1994, p. 3614)

The UFF test would also test for the Fifth Force. The paper of Su et al. quoted above, for example, sets limits on possible violations of Newton’s law of universal gravitation and on a possible Fifth Force, but did not cite the 1986 paper of Fischbach and collaborators.

In this epilogue I will concentrate on the experimental work that has relevance for the Fifth Force which has taken place since the funeral at Moriond. This is not intended to be a complete history but rather to give the flavor of the variety of experimental work done on the Fifth Force at the end of the twentieth century and the beginning of the twenty-first century. We will find that the Fifth Force is still dead.[21]

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[20] With apologies to George Lucas.

[21] I will not discuss several fascinating proposed experiments, which were never performed. For details of these proposals and for a more detailed history, see (Franklin and Fischbach 2016).

7.3.1 The 1990s

One of the earliest of these later experiments was performed by a group in China (Yang et al. 1991). The experimenters measured the differences in the acceleration due to gravity at various distances from an empty oil reservoir caused by filling or emptying the reservoir with water.[22] The acceleration was measured with a LaCoste-Romberg gravimeter, the standard apparatus used in earlier tower experiments. The experimenters compared the measured differences in acceleration with those calculated from Newtonian gravity alone. Any difference would be attributed to the Fifth Force. Their results are shown in Table 7.1. No differences between the measured and calculated values were seen. The group concluded, "It is worth pointing out that a weak intermediate-range interaction of Yukawa form is not excluded by our data but the possible strength of such an interaction is highly constrained $|\alpha| < 0.002$. This is in agreement with the results of the WTVD [Eckhardt's group] and BREN [Lawrence Livermore group] tower gravity experiments" (Yang et al. 1991, p. 332).[23]

There were also replications of previous types of experiment. Liu et al. (1992) measured the acceleration due to gravity as a function of height on a 320 m tower. This would test the possible distance dependence of the Fifth Force. They noted the previous discord between the early positive results reported by Eckhardt and his collaborators and the negative results reported by the Lawrence Livermore group, by Speake et al. (1990), by the later results of Eckhardt's group, and by others including Cruz et al. (1991). They remarked, "Many have questioned the results of Eckhardt et al. including Thomas et al. [the Livermore group] who, in an independent tower (BREN tower) experiment, found no evidence for non-Newtonian gravity. More recently Eckhardt et al. have revised their analysis and now their results appear consistent with Newtonian gravity. The newer and more precise Erie tower results

Table 7.1 Gravimetric measurements from Yang et al. (1991)

Distance from central axis of water cylinder (m)	Mean experimental value Δg_e and its standard deviation (10^{-5}m/s^2)	Newtonian prediction Δg_N (10^{-5}m/s^2)	$\Delta g_e/\Delta g_N$
10.00	0.424±0.002	0.423	1.002±0.005
20.00	0.273±0.002	0.272	1.004±0.007
30.00	0.146±0.002	0.145	1.007±0.014
40.00	0.075±0.002	0.073	1.027±0.027
50.00	0.040±0.003	0.038	1.053±0.079

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[22] This was similar to Bennett's experiment at the lock on the Snake River, discussed earlier.

[23] These were discussed earlier.

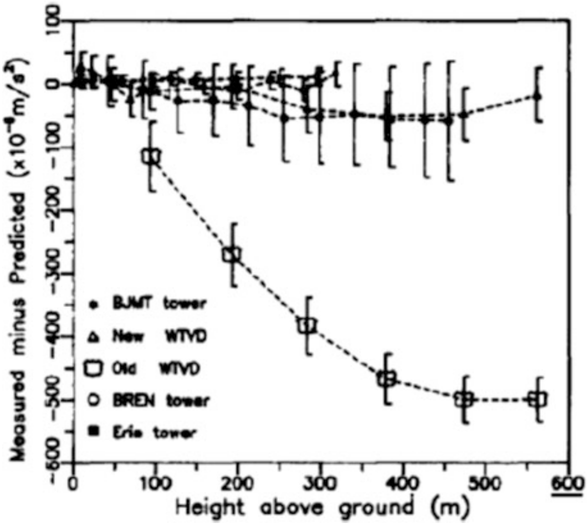

Fig. 7.14 Measured minus predicted values of the acceleration due to gravity as a function of the height aboveground for various tower experiments. From Liu et al. (1992).

of Cruz et al. (1991) now set a little stronger constraints on such a kind of non-Newtonian force. We decided that an independent experiment would help clarify the situation, and undertook to perform a tower test of gravity" (Liu et al. 1992, p. 131).

The experimenters used the standard LaCoste-Romberg gravimeter and corrected their results for tides, drift, gravimeter screw errors, and systematic effects due to tower motion. (All measurements were done at wind speeds less than 3 m/s). They stated that their tower was stable and located on a nearly flat terrain. Their results are shown in Figure 7.14 along with both the old and new results of Eckhardt et al. (1988) and several of the newer results. They concluded, "In a tower test of Newton's inverse square law of gravitation we found no evidence for the non-Newtonian force, and the accuracy of the experiments constrains the Yukawa potential coupling constant $|\alpha|$ to be less than 0.0005" (Liu et al. 1992, p. 131).

Carusotto and et al. (1992) performed an interesting variant on the Galileo-type free fall experiments discussed earlier. They measured the angular acceleration of a disk which had a half-disk of aluminum and a half-disk of copper (Figure 7.15): "If there is a difference Δg in the free-fall acceleration of aluminum and copper, then the disk assembly experiences a torque and, therefore there is an angular acceleration of the disk assembly ..." (Carusotto and et al. 1992, p. 1723). The disk would rotate. The acceleration was measured using laser light reflected from corner reflectors placed on the disk. The experimenters checked the sensitivity of their apparatus and looked for possible systematic effects by first making measurements with a disk made only of aluminum. They found $\Delta g/g = (3.2 \pm 9.5) \times 10^{-10}$, consistent with zero, demonstrating that there were no large systematic effects. Using the half-copper half-aluminum disk, they found $\Delta g/g = (8.5 \pm 9.5) \times 10^{-10}$ and $\Delta g/g = (-4.8 \pm 11.2) \times 10^{-10}$ with the disk reversed. They combined the two sets of measurements and set a limit of $\Delta g/g = (2.9 \pm 7.2) \times 10^{-10}$. "The result is compatible with zero (no g violation) and it is in quite good agreement with the one obtained by Kuroda and Mio for the same materials" (Carusotto and et al. 1992, p. 1725).

Experimental tests of the Fifth Force hypothesis continued in 1993. The group at the Tata Institute, using a torsion pendulum, sets more stringent limits on the possible coupling to isospin. Their 2σ limit for the strength was $-5.9 \times 10^{-5} \leq \alpha_I \leq 3.44 \times 10^{-5}$, "the best upper limit on α_I for all the experiments so far" (Unnikrishnan 1993, p. 408). Carusotto and collaborators reported further results on their falling-disk experiment (Table 7.2). In this experiment they used a copper-tungsten disk, rather than a copper-aluminum disk. They concluded, "There is no evidence for any g-universality violation, at the level of μGal, at least with the Galileo-type experiment performed so far" (Carusotto et al. 1993, p. 357).

In 1994 Eckhardt's group[24] published results on measurements of the acceleration due to gravity as a function of the height of the measurement on a tower, using a tower different from the one they had used in their previous experiments (Romaides

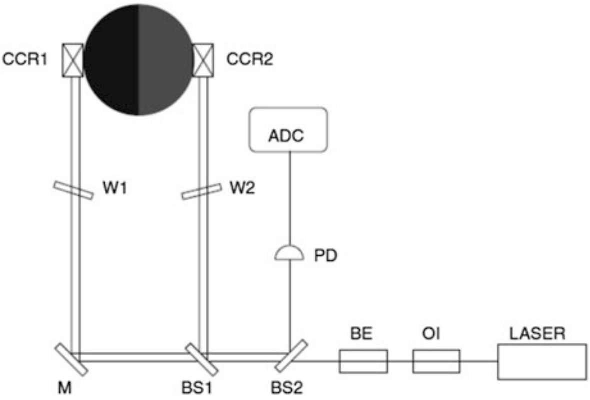

Fig. 7.15 Schematic diagram of the Galileo-type experiment for a disk composed of two different metals. From Carusotto et al. (1993).

Table 7.2 From Carusotto et al. (1993)

References	Compared materials	$\Delta g (\mu\text{Gal})$
Present work	Cu-W	0.71 ± 0.91
Carusotto and et al. (1992)	Al-Cu	0.29 ± 0.72
	Al-Cu	-0.13 ± 0.78
	Al-Be	0.43 ± 1.23
Kuroda and Mio (1990)	Al-C	-0.18 ± 1.38
Niebauer et al. (1987)	Cu-U	0.13 ± 0.5

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[24] The group also included Fischbach and Talmadge, two of the initial proposers of the Fifth Force hypothesis.

et al. 1994). They noted that they had initially obtained results at the WTVD tower in North Carolina which showed an apparent violation of Newtonian gravitation but that their later results, along with those of other tower experiments, had shown that Newton's law of gravity was valid over a range from 10 m to 10 km. They stated that, "Two of the major difficulties in the experiment were the inaccessibility of some areas around the WTVD tower, and the lack of a good terrain model, which meant that some computations could not be done as rigorously as desired" (Romaides et al. 1994, p. 3608). Their new results were obtained at the WABG tower in Mississippi, which had the advantage of very flat local terrain and easy access for gravity measurements near the tower. They concluded, "The tower observations were compared to the predictions, with the largest discrepancy being $-33 \pm 30 \mu$Gal at 493 m. The results are in good agreement with previous tower experiments, which also are in accord with the inverse-square law, and they set further restrictions on possible non-Newtonian forces"(Romaides et al. 1994, p. 3608). The group reported that their WABG results agreed not only with their last WTVD tower results but also with the results of other tower experiments (Figure 7.16). They stated that they were ending their investigations[25] and that "... we have learned from these and other experiments that there is no credible evidence for deviations from the inverse-square law over a laboratory to solar system scale length. By helping to fill in the scale $\lambda \approx 10^3$ m, tower experiments have thus played an important role in confirming our belief in the validity of Newtonian gravity" (Romaides et al. 1994, p. 3612).

The inclusion of tests of the Fifth Force as part of more general experimental work on general relativity and its implications became clear in the 1994 report of the Eöt-Wash group mentioned earlier (Su et al. 1994). The experimenters stated purpose was to measure the universality of free fall with respect to the Earth, the

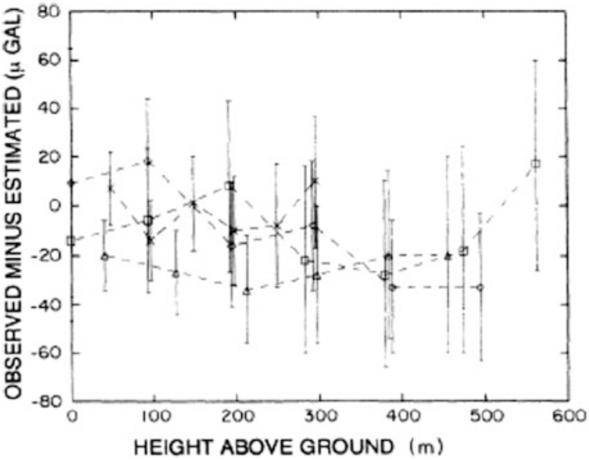

Fig. 7.16 The observed-minus-model discrepancies for all tower experiments along with their associated la errors. The diamonds are the WABG results; the boxes are the WTVD results; the triangles are the BREN tower results; and the crosses are the Erie tower results. In order to avoid clutter, not a11 data points were plotted. Note the excellent agreement especially at the upper elevations. From Romaides et al. (1994).

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[25] As we shall see below, this is not quite accurate.

Table 7.3 Comparison of the 1991 (Adelberger et al. 1991) and 1994 (Su et al. 1994) Eöt-Wash results

	$\alpha\Delta(B/\mu)_{\text{detector}}$ $(B/\mu)_{\text{source}}\lambda = 30$ m	$\lambda = 20$ m	$\lambda = 50$ m
1991	$(1.4 \pm 2.9) \times 10^{-8}$		
1991	$(-2.1 \pm 3.6) \times 10^{-8}$		
1994 (Be-Al detector)		$(-0.5 \pm 1.1) \times 10^{-8}$	$(-2.6 \pm 5.4) \times 10^{-9}$
1994 (Be-Cu detector)		$(-11 \pm 9.8) \times 10^{-9}$	$(-5.3 \pm 4.8) \times 10^{-9}$

Sun, our galaxy, and in the direction of the cosmic microwave dipole.[26] They further noted that, "Our galactic-source results tests the UFF [Universality of free fall] for ordinary matter attracted toward dark matter ..." (Su et al. 1994, p. 3614).[27]

The experimental group had made improvements in their torsion balance apparatus including better regulation of the turntable speed, compensation for gravity gradients, and in the calibration of their instruments. Although the Fifth Force is not explicitly mentioned, nor is the paper of Fischbach et al. (1986a) cited, the Eöt-Wash results did provide more stringent limits on the presence of such a force. It is difficult to make a direct comparison between the earlier and later results because the 1991 Eöt-Wash paper presented a limit on a force with a range of 30 m, whereas their 1994 paper gave limits for both 20 m and 50 m. The results are shown in Table 7.3. One can see that the uncertainty in the results has improved by a factor of approximately three and were consistent with no Fifth Force.

A group at the University of Zurich reported another test of the Fifth Force (Cornaz et al. 1994).[28] The experiment measured the difference in weight between two masses as a function of the height of the water in a pumped storage reservoir, Lake Gigerwald (Figure 7.17). "The basic idea of the Gigerwald experiment was to measure the weight difference of two test masses located above and below the variable water level with a single balance" (Cornaz et al. 1994, p. 1152). The experimental design avoided several of the problems of such experiments. "Since the weight difference is measured in a short time, balance drifts are negligible. Time-variable gravity effects originating from distances much larger than the separation of test masses completely vanish (e.g., tides). By comparing the weight differences

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[26] The title of the paper was, "New tests of the universality of free fall."

[27] The group also stated that, "We also test Weber's claim that solar neutrinos scatter coherently from single crystals with cross sections $\sim 10^{23}$ times larger than the generally accepted value and rule out the existence of such cross sections" (Su et al. 1994, p. 3614). For a more detailed history of this episode, see Franklin (2010).

[28] The major purpose of the experiment, as the title of the paper reveals, was to measure *G*, the gravitational constant.

Fig. 7.17 Schematic view of the Gigerwald experiment. From Cornaz et al. (1994).

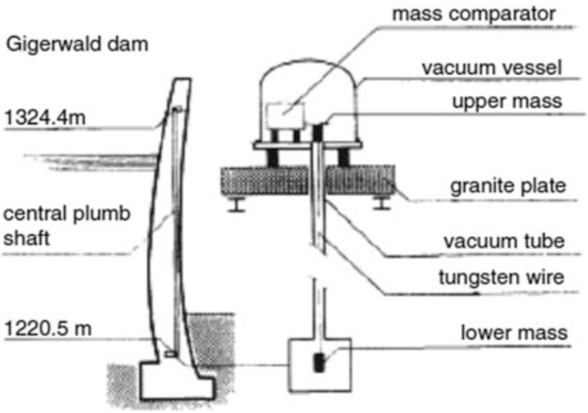
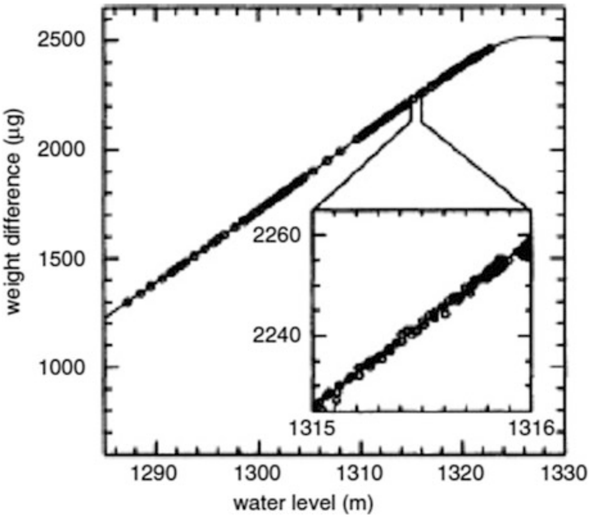


Fig. 7.18 The solid curve is the calculated weight difference of the two test masses as a function of the water level following pure Newtonian gravity (the origin is set at 1240 m for an empty lake). From Cornaz et al. (1994).



at several water levels even the static local gravity from the surroundings cancels. Finally, the recorded gravity signal is just due to the interaction between the locally moved mass (water and air) and the test masses" (Cornaz et al. 1994, pp. 1152–1153). The comparison between the theoretically calculated weight differences and the measured values is shown in Figure 7.18. The experimenters obtained more stringent limits on α, the strength of the proposed force, as a function of λ, the range, than had been obtained in previous experiments (Figure 7.19).[29]

Experimental work on tests of the Fifth Force slowed, although there was still considerable theoretical work. In 1996 Carusotto et al. (1996) published their final results, which were the same as those discussed earlier, except for the inclusion of

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[29] This experiment was similar to those of Moore et al. (1988) and Bennett (1989).

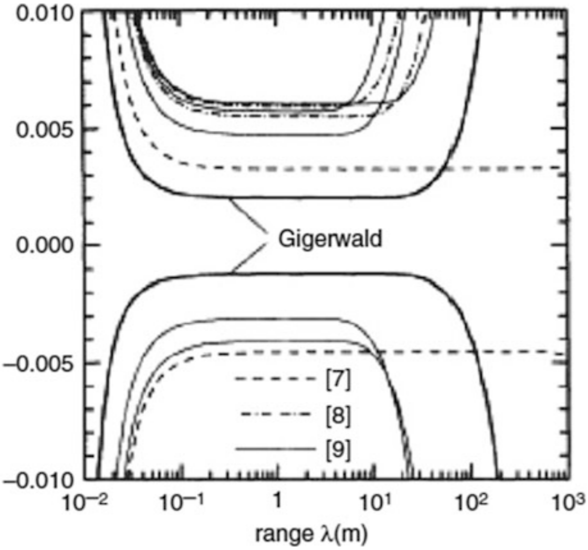

Fig. 7.19 Excluded strengths α and ranges λ for a single Yukawa model at the 20 level arising from experiments measuring directly the gravitational constant at geophysical distances. From Cornaz et al. (1994).

a small systematic uncertainty. They concluded, "There is no evidence of any g-universality violation, at the level of μGal, at least with Galileo's type experiment performed so far" Carusotto et al. (1996, p. 1274).

In 1997 Romaides et al. published their final results from the WABG tower experiment (Romaides et al. 1997). They had overcome the difficulties in making measurements at the largest height and stated, "…we succeeded in obtaining readings at 568 m above ground level. These readings, along with the previous results on the WABG and WTVD towers, allow for even tighter constraints on the non-Newtonian force parameters α and λ [the strength and range of the proposed Fifth Force]. Furthermore, we can now combine our tower data with data from lake experiments to give very tight constraints on the non-Newtonian coupling constant α over the entire geophysical window (10 m to 10 km)" (Romaides et al. 1997, p. 4352). Those constraints are shown in Figure 7.20. They concluded, "In summary, we conclude from existing tower experiments that at the present time there is no evidence for any significant deviation from the inverse-square law for $\lambda \approx 10^3$ m" (Romaides et al. 1997, p. 4356).

The Eöt-Wash group reported a new result using an interesting variant on their previous experimental apparatus (Gundlach et al. 1997). In their previous work, the group had used a torsion balance mounted on a rotating platform to measure the differential acceleration of various substances toward a local hillside and to other sources such as the Sun, the Earth, and the galaxy. In their latest experiment, the experimenters used a rotating three-ton ^{238}U attractor to measure the differential acceleration of lead and copper masses placed on a torsion balance. The Röt-Wash[30] apparatus is shown in Figure 7.21. The surroundings of the torsion balance

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[30] The Eöt-Wash group continued its whimsy with the naming of their new apparatus.

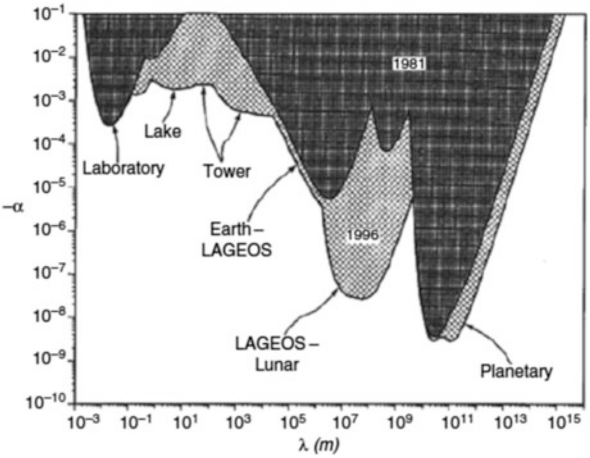

Fig. 7.20 Constraints on α in the range 10 m to 10 km. From Romaides et al. (1997).

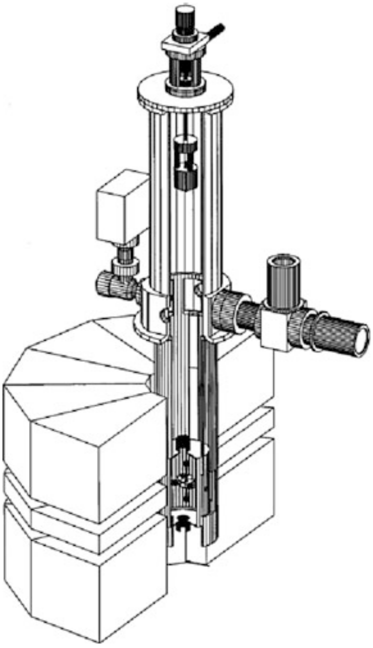

Fig. 7.21 Schematic view of the Röt-Wash instrument. The ^{238}U was counterbalanced by 820 kg of lead, so the floor would not tilt as the attractor revolved. From Gundlach et al. (1997).

were temperature controlled to guard against possible temperature effects. The ^{238}U was counterbalanced by 820 kg of lead, so the floor would not tilt as the attractor revolved. Tilt was a significant source of possible background effects in the Eöt-Wash experiments. The reason for the modification of the apparatus was that their previous experiment (Su et al. 1994) had been unable to test for forces with a range from 10 km to 1000 km. The new apparatus, using a local source, allowed such a test. The experimenters concluded, " We found that $a_{\mathrm{Cu}} - a_{\mathrm{Pb}} = (-0.7 \pm 5.7) \times 10^{-13}$ cm/s^2, compared to the 9.8×10^{-5} cm/s^2 gravitational acceleration toward the attractor. Our results set new constraints on equivalence-principle violating interactions with Yukawa ranges down to 1 cm and rule out an earlier suggestion of a Yukawa interaction coupled predominantly to N – Z" (Gundlach et al. 1997, p. 2523).

In 1997 George Gillies published a review of measurements of the gravitational constant and other related measurements. He remarked that, "The contemporaneous suggestion by Fischbach et al. (1986a) that there may be previously undiscovered, weak, long-range forces in nature provided further impetus for investigating the composition- and distance-dependence of gravity, since the presence of any such effect might reveal the existence of a new force. During this time, a theoretical framework for admitting non-Newtonian effects into discussions of the experimental results was emerging. It led to the practice of using the laboratory data to set limits on the size of the strength-range parameters in a Yukawa term added onto the Newtonian potential, and this has become a standard method for intercomparing the results of this class of experiments. Even though convincing evidence in favour of such new weak forces was never found, the many resulting experiments, when viewed as tests of the universality of free-fall, did much to improve the experimental underpinnings of the weak equivalence principle (WEP) of general relativity. In fact, searches for departures from the inverse square behaviour of Newtonian gravity have now come to be interpreted as attempts to uncover violations of the WEP" (Gillies 1997, p. 200).

After a decade of negative experimental results of the Fifth Force, 1997 produced a positive result. Achilli et al. (1997), using a superconducting gravimeter, measured changes in the gravitational force caused by the changing water level in a pumped storage reservoir, Lake Brasimone in Italy, and found evidence for a violation in the distance dependence of Newton's law (Figure 7.22). The superconducting gravimeter could measure variations in gravity of the order of 1 nGal (1 Gal = 1 cm/s^2). A problem for the experimenters was the fact that tidal effects were of the order of 100–250 μGal. That effect could not be calculated precisely, so the group measured the lake tides for a period of 5 months at a location 400 m from the lake. The experimenters also obtained a detailed survey of the lake shore, an important factor in obtaining a result.

The gravimeter measured the gravitation effect by measuring the feedback force needed to maintain a levitated superconducting niobium sphere in a fixed position (Figure 7.23). They calibrated their apparatus by moving a known annular mass vertically with the gravimeter at its center. They also compared their gravimeter to an absolute gravimeter from another laboratory. The experimenters also investigated

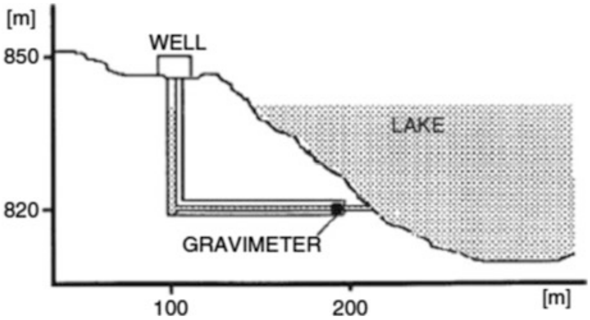

Fig. 7.22 Sketch of the Lake Brasimone experiment. From Achilli et al. (1997).

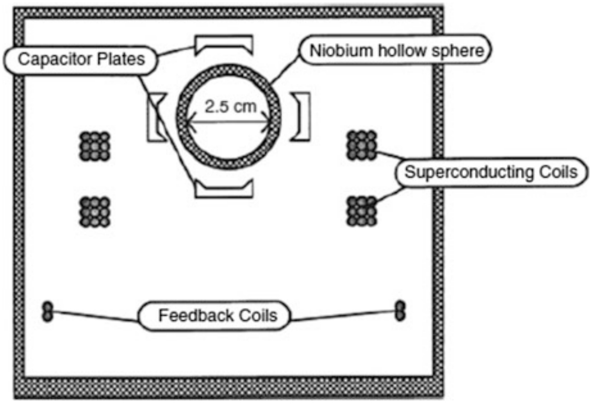

Fig. 7.23 Schematic cross-sectional view of the gravity sensor. The entire apparatus is contained in a liquid helium bath. From Achilli et al. (1997).

and measured geological, temperature, water table, and density background effects. Their final result R = observed/theoretical effect was 1.0127±0.0013 (Figure 7.24). "The ratio between the measured and expected gravitational effects differs from 1 by more than 9 standard deviations" (Achilli et al. 1997, p. 775). The experimenters noted, however, that, "… the only parameter not verified at the 0.1% level was the gravimeter calibration factor. In any case, the adopted value is in agreement with the result of the comparison with an absolute gravimeter" (Achilli et al. 1997, p. 802). Their results for $|\alpha|$ as a function of λ are shown in Figure 7.24. The group stated that their result differed from that found by Cornaz et al. (1994) in a similar experiment (see earlier discussion).

7.3.2 *The Twenty-First Century*

The Eöt-Wash group continued taking data with their rotating ^{238}U attractor. They remarked that, "Our new results set new constraints on equivalence principle violating interactions with Yukawa ranges down to 1 cm, and improved by substantial factors existing limit for ranges between 10 km and 1000 km" (Smith et al. 2000,

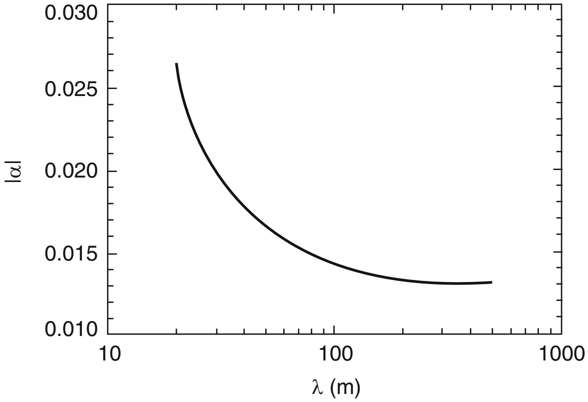

Fig. 7.24 $|\alpha|$ versus λ in the range 20 m to 500 m. From Achilli et al. (1997).

p. 022001-1). Their results are shown in Figure 7.25. Their new value for the difference in acceleration for copper and lead masses was $a_{\text{Cu}} - a_{\text{Pb}} = (-1.0 \pm 2.8) \times 10^{-13}$ cm/s^2, with the uncertainty reduced by a factor of two compared to their 1997 result.

Perhaps the most interesting result reported in 2000 was the withdrawal of the positive Fifth Force result of Achilli et al. (1997). As Focardi, a member of the group remarked, "The above result [the positive result] convinced us of the importance of making any possible effort to check the conclusions reached in the previous experiment" (Focardi 2002, p. 419).[31] This withdrawal was based on a reanalysis of the same data used in the 1997 paper. (A more detailed discussion of the reanalysis appeared in Baldi et al. 2001.) The experimenters performed a new and better calibration of their superconducting gravimeter and included a more consistent model of tidal gravity variations. Their initial paper had stated that "the only parameter not verified at the 0.1% level was the gravimeter calibration factor" (Achilli et al. 1997, p. 802). Their new result for R = experimental value/theoretical calculation $= 1.0023 \pm 0.0017$. This should be compared with their earlier result of $R = 1.023 \pm 0.0017$. They concluded that, "The result of this analysis shows an agreement between data and Newtonian theory to within 0.1 % level" (Baldi et al. 2001, p. 082001-2). At the turn of the twenty-first century, there was still no evidence supporting the Fifth Force.

In 2001 Bennett reported a second result from his experiment conducted at the Little Goose Lock on the Snake River. This was a torsion pendulum experiment which used the changing amount of water in the lock as an attractor. His initial data was taken in 1988 and published in 1989 (Bennett 1989). His 2001 paper included additional data taken in 1990.[32]

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[31] Focardi's paper was presented at a conference in 2000, but the conference proceedings were not published until 2002.

[32] For various personal reasons, Bennett did not publish these results until 2001.

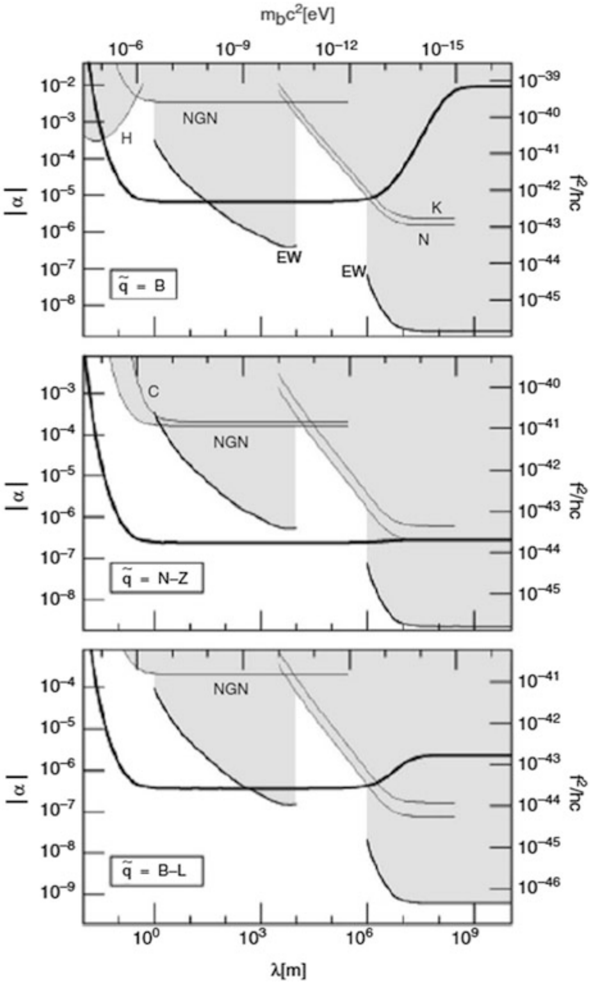

Fig. 7.25 95% confidence limits on $|\alpha|$ vs λ for hypothetical interactions coupling to vector charges $q = B, q = N - Z$, or $q = B - L$, where B is baryon number, N is the number of nucleons in the nucleus, Z is the number of protons, and L is the number of leptons. The heavy curves are from this work. From Smith et al. (2000).

Bennett had made improvements in his apparatus including replacing the copper-lead disk in his torsion pendulum with a copper-lead annular ring. "A $2 - \sigma$ limit was set on the "isospin coupling constant" of $\alpha_0 = \pm 0.001$ at $\lambda = 100$ m" (Bennett 2001, p. 123). He also presented a summary of the $1 - \sigma$ limits on the differential acceleration for various pairs of substances (Table 7.4) along with a comparison of the coupling constants, α_0, obtained by various experiments (Figure 7.26). The Fifth Force was still absent.

Despite the negative evidence, new experimental tests of the Fifth Force and of the weak equivalence principle were still being planned. Dittus and Mehls (2001), for example, were building a free-fall experiment in which two test masses of different substances would be dropped from a height of 110 m at the Bremen Tower. Any difference in fall would be detected by a SQUID (superconducting quantum

Table 7.4 Comparison of 1-σ limits on differential acceleration From Bennett (2001)

Reference	$\Delta a \times 10^{10}$cm/sec^2	Test masses	Source
(Thieberger 1987)	850 ± 260	Cu-H_20	Cliff
(Fitch et al. 1988)	30 ± 49	Cu-CH_2	Sloping terrain
(Bennett 1989)	25 ± 52	Cu-Pb	H_20
(Bennett 2001)	2 ± 22	Cu-Pb	H_20
(Adelberger et al. 1990)	-0.15 ± 2.6	Be-Al	Pb

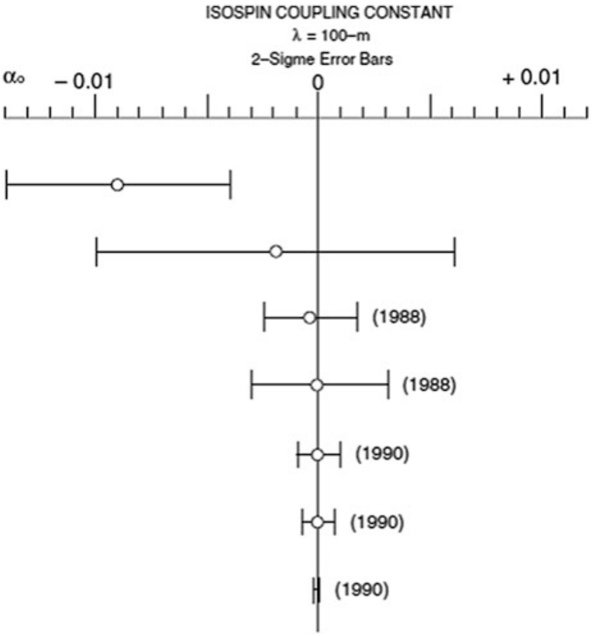

Fig. 7.26 Comparison of different determinations of the intrinsic coupling coefficient α_0 for isospin coupling. From Bennett (2001); note that "BENNETT (1990)" is Bennett (2001).

interference device). They were aiming at an accuracy of better than 10^{-12} in the Eötvös ratio $\eta = 2((m_g/m_i)_1 - (m_g/m_i)_2)/((m_g/m_i)_1 + (m_g/m_i)_2)$, where m_i and m_g are the inertial and gravitational masses and the indices 1 and 2 are for the test masses of different substances. They remarked that the then current best value for η was less than 10^{-12} obtained by the Eöt-Wash group (Su et al. 1994).

Reasenberg and Phillips were developing a different type of apparatus. "We are developing a Galilean test of the equivalence principle in which two pairs of test mass assemblies (TMA) are in free fall in a comoving vacuum chamber for about 0.9 s. The TMA are tossed upward, and the process repeats at 1.2 s intervals.[33] Each TMA carries a solid quartz retroreflector and a payload mass of about one-third of the total TMA mass. The relative vertical motion of the TMA of each

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[33] The title of their paper is "Testing the equivalence principle on a trampoline."

pair is monitored by a laser gauge working in an optical cavity formed by the retroreflectors. Single-toss precision of the relative acceleration of a single pair of TMA is 3.5×10^{-12} g. The project goal of $\Delta g/g = 10^{-13}$ can be reached in a single night's run" (Reasenberg and Phillips 2001, p. 2435).

In 2002 as part of a proposed satellite experiment to test the weak equivalence principle, Moffat and Gillies summarized the current state of such tests. "In a long series of elegant experiments with rotating torsion balances, the Eöt-Wash Group has searched for composition dependence in the gravitational force via tests of the universality of free fall. In terms of the standard Eötvös parameter η, they have reached sensitivities of $\eta \sim 1.1 \times 10^{-12}$ in comparisons of the accelerations of Be and Al/Cu test masses and, more recently, have resolved differential accelerations of approximately 1.0×10^{-14} cm s^{-2} in experiments with other masses. Drop-tower experiments now underway in Germany have as their goal testing WEP at sensitivities of $\eta \sim 1 \times 10^{-13}$, and Unnikrishnan describes a methodology under study at the Tata Institute of Fundamental Research in India wherein torsion balance experiments aiming at sensitivities of $\eta \sim 1 \times 10^{-14}$ are being developed" (Moffat and Gillies 2002, p. 92.3). None of these experiments provided evidence for the Fifth Force. The authors noted that proposed space-based experiments expected greater sensitivity. It was not clear, however, whether such experiments would cast any light on the Fifth Force, as initially proposed.

There were no other significant experimental tests of the Fifth Force in the early part of the twenty-first century. There were, however, experiments to measure G, the universal gravitational constant, a parameter whose value was then, and is now, uncertain. There were also experiments testing the law of gravity at very short distances, as well as continued discussions of space experiments. In 2005, Jens Gundlach, a member of the Eöt-Wash collaboration, published a review of the evidence to that date. His conclusion was, "At the moment, no deviations from ordinary gravity have been found, ..." (Gundlach 2005, p. 21). Faller (2005) published an amusing review of measurements of g, the acceleration due to gravity at the surface of the Earth. Faller and his collaborators had previously tested the Fifth Force hypothesis in both Galileo-type falling body experiments and by measuring g as a function of height in a tower. He noted that, "In the end (numerous experiments by many workers later), Newtonian gravity was vindicated" (Faller 2005, p. 571). He also related an amusing anecdote concerning the use of the tower in Erie, Colorado in the tests of the inverse-square law of gravity. "NOAA asked a modest \$1000 in rent for our use of the tower. Their other requirement was that we sign a paper to the effect that if we fell off in the course of making measurements, NOAA would not be held responsible for any personnel free falling due to gravity" (Faller 2005, p. 571).

The Eöt-Wash collaboration continued their extensive study of the equivalence principle with a new and improved torsion balance (Schlamminger et al. 2008). Their results for the difference in acceleration for beryllium and titanium test masses, in the northern and western directions, are shown in Figure 7.27. A violation of the equivalence principle would appear as a difference in the means of the runs taken with the masses in different orientations. The small offset was due to a systematic error, which did not affect their conclusion. Their new upper limits for α, the strength parameter for the Fifth Force or any other deviation from the

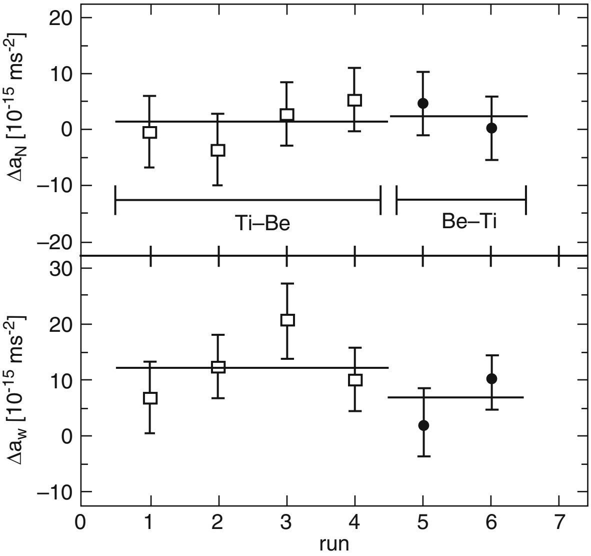
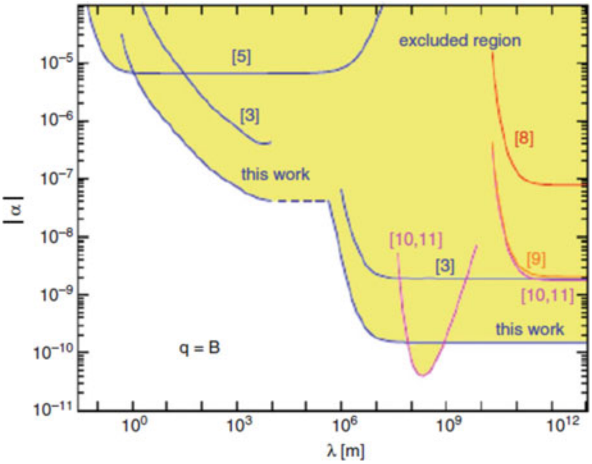


Fig. 7.27 Shown are measured differential accelerations toward north (top) and west. After the first four data runs, the Be and Ti test bodies were interchanged on the pendulum frame. A violation of the equivalence principle would appear as a difference in the means (lines) of the two data sets. The offset acceleration is due to systematic effects that follow the pendulum frame but not the composition dipole. From Schlamminger et al. (2008).

Fig. 7.28 New upper limits on Yukawa interactions coupled to baryon number with 95% confidence. From Schlamminger et al. (2008).



law of gravity, are shown in Figure 7.28. The region of interest for the Fifth Force is at approximately 100 m.[34] "We used a continuously rotating torsion balance instrument to measure the acceleration difference of beryllium and titanium test bodies towards sources at a variety of distances. Our result $\alpha_{\text{N,Be-Ti}} = (0.6 \pm 3.1) \times 10^{-15}$ m/s^2 improves limits on equivalence-principle violations with ranges from 1 m to ∞ by an order of magnitude. The Eötvös parameter is $\eta_{\text{Earth,Be-Ti}} = (0.3 \pm 1.8) \times 10^{-13}$" (Schlamminger et al. 2008, p. 041101-1). Recall that their previous best limit for η was 1.1×10^{-12}. The Fifth Force, if it existed, was becoming weaker.

In 2009 a review paper on torsion balance experiments by members of the Eöt-Wash group appeared (Adelberger et al. 2009; Gundlach et al. 2009). Adelberger and collaborators discussed details and experimental issues involved in torsion balance experiments as well as past experiments and proposed future experiments. The "Fifth Force" era received only a very brief summary. "After the completion of the classic experiments,[35] little further activity took place until 1986 when Fischbach et al. (1986a) reanalysed the Eötvös data. They used this, along with previous claims of anomalous data on g in mines, to claim evidence for a new force. This "Fifth Force" was an EP-violating acceleration coupled to B with a range of a few hundred meters that would have rendered it invisible to the classic solar EP tests. This finding triggered many experiments looking for intermediate-range ($10 \text{ m} < \lambda < 10000 \text{ km}$) forces. The Eöt-Wash group at the University of Washington responded by developing a torsion balance mounted on a uniformly rotating platform .... The first result from this instrument, which appeared in 1987, ruled out the original Fifth Force proposal.[36] However, the suggestion of a finite-ranged Yukawa interaction led physicists to broaden their view of EP tests to a search for Yukawa interactions at all accessible length scales" (Adelberger et al. 2009, pp. 108–109).

After 2010 there was very little experimental activity that explicitly dealt with the Fifth Force. This is not to say that there was no work on the related topic of the universality of free fall and tests of the weak equivalence principle. Various experiments conducted in space tested that principle at distances larger than the range of the Fifth Force, and there were laboratory experiments that investigated the law of gravity at much smaller distances. An entire issue of *Classical and Quantum Gravity* (Volume 29, Issue 18, 2012) was devoted solely to tests of the weak equivalence principle. The Eöt-Wash group paper in that volume reported a new result (Wagner et al. 2012). In addition to their previous result of $\alpha_{\text{N,Be-Ti}} =$

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[34] This was the approximate range suggested in the initial paper, based on the (later withdrawn) results of Stacey and his collaborators. The data of the Eötvös and his collaborators is consistent with ranges up to 1 AU.

[35] These were the experiments which test the weak equivalence principle in the fall of bodies toward the Sun: Braginskii and Panov (1972) and Roll et al. (1964).

[36] As we saw in Section 7.2 and in the history presented above, this is not accurate.

$(0.6 \pm 3.1) \times 10^{-15}$ m/s^2, they presented a new result for an aluminum-beryllium pair, $\alpha_{\text{N,Be-AL}} = (-1.2 \pm 2.2) \times 10^{-15}$ m/s^2.

Will (2014) summarized the situation with respect to the Fifth Force in an extensive review, "The Confrontation between General Relativity and Experiment." He concluded that, "A consensus emerged that there was no credible evidence for a fifth force of nature, of a type and range proposed by Fischbach et al." (Will 2014, p. 27). Will's summary is, as we have seen, accurate.

7.3.3 Discussion

There is very strong and persuasive evidence that the Fifth Force, as initially proposed by Ephraim Fischbach and his collaborators, does not exist. Numerous experiments have not shown the presence of any force with strength approximately one percent that of Newtonian gravity and with a range of about 100 m. I believe, however, that the hypothesis has been quite fruitful. It encouraged renewed interest in tests of general relativity, particularly on the weak equivalence principle and on Newtonian gravity at both very large and very small distances and on its composition dependence. This work also led to improvements in both experimental apparatuses and experimental analyses. As Gillies remarked in 1997, "The contemporaneous suggestion by Fischbach et al. (1986a) that there may be previously undiscovered, weak, long-range forces in nature provided further impetus for investigating the composition- and distance-dependence of gravity, since the presence of any such effect might reveal the existence of a new force .... Even though convincing evidence in favour of such new weak forces was never found, the many resulting experiments, when viewed as tests of the universality of free-fall, did much to improve the experimental underpinnings of the weak equivalence principle (WEP) of general relativity. In fact, searches for departures from the inverse square behaviour of Newtonian gravity have now come to be interpreted as attempts to uncover violations of the WEP" (Gillies 1997, p. 200).

Some scholars have suggested that the Fifth Force hypothesis should never have been further investigated (Anderson 1992). These after-the-fact judgments are, I believe, incorrect. As mentioned above the hypothesis was quite fruitful. In addition, I believe that it is important to recognize that wrong science is not bad science. The fact that the Fifth Force hypothesis turned out to be incorrect is not a good reason for saying that it should not have been further investigated. There was, at the time, plausible evidence from the reanalysis of the Eötvös experiment, from the discrepancy between laboratory and mineshaft measurements of g and from the tantalizing energy dependence of the K^0 decay parameters that was consistent with the hypothesis. Although one might argue that it was an unlikely hypothesis, the history of science has shown that on occasion such hypotheses have turned out to be correct. Consider the case of parity nonconservation. Distinguished scientists such as Wolfgang Pauli and Richard Feynman were willing to bet that the suggestion by

Lee and Yang that parity was not conserved in the weak interactions was incorrect. Feynman bet Norman Ramsey 50 to 1 that parity would be conserved. When experiments showed that parity was not conserved, Feynman paid (for details see Franklin 1986, Chapter 1).

The episode of the Fifth Force is an illustration of good science. A speculative hypothesis, one with some evidential support, was proposed. Further experimentation demonstrated that the hypothesis was incorrect. It did, however, lead to further experimental and theoretical work and improvements in experiments.

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