THE ARGUMENTS AGAINST “ANTIGRAVITY” AND THE GRAVITATIONAL ACCELERATION OF ANTIMATTER

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Abstract:

In the 1950's interest arose in the science-fiction idea of "antigravity". This concept was a speculation that matter and antimatter would repel each other in ordinary tensor (Einsteinian) gravity. (This was reminiscent of the Coulomb interaction between like charges.) Three types of arguments were raised to disprove "antigravity": (i) violation of conservation of energy, (ii) violation of the principle of equivalence, (iii) anomalous regeneration of K_S mesons, all of which were unseen. Unfortunately, in the physics folklore these arguments came to be interpreted as ruling out *any* difference in the gravitational interaction of matter and antimatter to the earth, not just ruling out this "antigravity."

After reviewing the history behind the concept of antigravity, we discuss modern theoretical ideas and experiments which are relevant to the possibility that there exist static, non-Newtonian components of gravity. We then consider the arguments against antigravity, pointing out their regimes of applicability and inapplicability to modern quantum theories of gravity. We specifically show that, if these arguments are applied to the ongoing experiment to measure the gravitational acceleration of the antiproton, they do not rule out a large anomalous gravitational response for the antiproton. The antiproton gravity experiment is one of five types of experiments that we consider to be the most critical in testing for finite but long-range, non-Newtonian and non-Einsteinian gravity. We discuss how all five are related to each other and how their completion would improve our knowledge of gravitational forces.

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* This review is dedicated to the memory of William Fairbank. His pioneering attempt to measure the gravitational acceleration of the positron was crucial to this field. Fairbank had strongly urged us to write this article.

1. Introduction

1.1. The concept of "antigravity"

This story can be said to have begun as Maxwell was completing his classical unification of electricity and magnetism. In his great article [Max65a], which completed the derivation of Maxwell's equations [Bor63; Sha73], Maxwell briefly turned to gravity [Max65b]. "After tracing to the action of the surrounding medium both the magnetic and the electric attractions and repulsions, and finding them to depend on the inverse square of the distance, we are naturally led to inquire whether the attraction of gravitation, which follows the same law of the distance, is not also traceable to the action of a surrounding medium."

But Maxwell also knew where the problem lay: in the charges. For electromagnetism, like charges repel and opposites attract. To make gravity similar to his vector theory (to use our modern parlance), Maxwell would have needed to reverse that. "Gravitation differs from magnetism and electricity in this; that the bodies concerned are all of the same kind, instead of being of opposite signs, like magnetic poles and electrified bodies, and that the force between these bodies is an attraction and not a repulsion, as is the case between like electric and magnetic bodies."

And what would be the result? "The intrinsic energy of the field of gravitation must therefore be less wherever there is a resultant gravitating force. (But,) as energy is essentially positive, it is impossible for any part of space to have negative intrinsic energy." This would have amounted to what we call runaway solutions. Therefore, Maxwell concluded, "As I am unable to understand in what way a medium can possess such properties, I cannot go any further in this direction in searching for the cause of gravitation." Maxwell, almost a century ahead of his time, had effectively ruled out "antigravity" on the basis of not conserving energy.

Of course, the modern idea of "antigravity" came about because of the two physics revolutions of this century: quantum mechanics and general relativity. (See the excellent reviews by Will [Wil84, 90b] and Cook [Coo88] for discussions, from different perspectives, of the theoretical versus experimental status of general relativity.)

From the particle-physics point of view, general relativity is a theory of gravity where the force is mediated by a tensor (spin-two) particle with the charge being mass–energy [Fey63]. Therefore, the force is always attractive. On the other hand, classical and quantum electromagnetism both have two charges, positive and negative. The forces are mediated by a vector (spin-one) field which produces an attractive force between opposite charges and a repulsive force between like charges. Physicists were thus led to wonder if a more general statement could be made. This was especially true for people in the late 1930's and early 1940's who were studying the nature of nuclear forces [Kem38; Møl40].

Many physicists who worked in that era [Bet82] have told us that it gradually came to be understood that charge-forces mediated by even-integer spin bosons are always attractive (scalar, tensor, etc.) whereas forces mediated by odd-integer spin bosons can be both attractive or repulsive, depending upon whether the charges are opposite or alike. However, none were able to give us a "prime source." The earliest publication we know of which made this statement was authored by Peaslee [Pea56], although more recent authors have also made this point [Fey63; Des67; Jag86].

Here the concept of antimatter entered. (See [Forw88] for a bibliography on antimatter.) As has been emphasized by Feynman [Fey87], given the existence of relativistic quantum mechanics, antimatter follows [Niet88a; Kra89]. The negative energy solutions of the Dirac equation were the initial indication. The positron was the first in a long series of discovered antiparticles, whose understanding culminated in the full fruition of the *CPT* theorem in 1957 [Lüd57; Sak64; Str64].

Gravity and antimatter were a combination which stimulated everyone. Could there be "antigravity" (or tensor-antigravity)? By this is meant that matter and antimatter repel each other due to a tensor gravitational interaction, with the sign of Newton's constant reversed. The idea of "antigravity" was of interest not only to members of the general public [Cla57], but also to scientists [Stue74]. Indeed, to scientists there was another stimulation, which came from cosmology.

When Einstein originally formulated his general theory of relativity, he added the possibility of a cosmological term. This was because he could think of no other way for the apparently static universe to be stable against gravitational collapse. But later, the Hubble expansion of the universe was discovered, removing the need for the cosmological term. This led to the Big-Bang theory of the universe [Gam52], which holds that the Hubble expansion is the result of a primordial explosion (now estimated to have occurred on the order of 20 billion years ago).

Although the big-bang theory had been reasonably well formulated by the late 1940's, there was then no way to test it. In this setting Bondi and Gold [Bon48], and independently Hoyle [Hoyl48, 49], proposed the Steady-State theory of the universe [Bon60]. This theory held that as the universe expanded there was a continuous creation of matter such that, on the average over large times, the average density of the universe was a constant. Therefore, there was a way to test this theory. At large distances the universe had to look the same age as in our local region and the Hubble expansion law had to be of a specific form. (Of course, much later the universe was found to be much different at large distances, with quasars extant, and also the 3 K black body radiation was discovered.)

The amount of matter needed to be created in the steady-state was small. Even in that period the estimate was on the order of one hydrogen atom per liter per 10^{12} years [Bon48]. But this did imply a very small violation of energy conservation. Therefore, nothing was more natural than to ask if there was a place for "antigravity". Indeed, Bondi did ask if there were valid negative-mass solutions in general relativity [Bon57].

However, in an historic study, Gold joined forces with Morrison to discuss the interplay of gravity and antimatter. This study resulted in the 1957 prize-winning essay of the Gravity Research Foundation [Mor58a]. Morrison elaborated on this work in his 1958 Richtmyer Lecture [Mor58b]. This paper contained the first of the three classic arguments against "antigravity".

Before proceeding to these three arguments against "antigravity", it is worthwhile to note a related question which arose during this period, that of the dominance of matter over antimatter in the universe. By 1956 one could not help noticing that there was a baryon–lepton asymmetry in our part of the universe; i.e., there was only matter in our neighborhood. One could conclude this from the lack of observed electron–positron annihilation photons in cosmic rays [Bur56]. Since one had come to expect the equations of physics to be *CPT*-invariant, one had to wonder why this asymmetry existed. Indeed, Goldhaber did [GolM56]. He wondered if the universe had separated into some galaxies (or clusters of galaxies) that are composed entirely of matter and others that are composed entirely of antimatter because of a long-range repulsion between matter and antimatter.

This speculation inspired Alfvén, who joined forces with Klein [Alf62], to propose a cosmology based on an electromagnetic plasma separation of matter and antimatter, aided by gravitational forces [Alf65, 66]. Today, as no experimental evidence for antimatter galaxies exists, we view the predominance of matter as a problem of the early universe. We now know that *CP* violation exists and we strongly conjecture that baryon and lepton numbers are not conserved individually, although they are perhaps conserved in the combination B–L. Therefore, we consider early universe scenarios where this

CP violation allows the universe to evolve to a dominance of matter over antimatter. (See the review by Dolgov and Zeldovich [Dol81] for a discussion of this problem.)

In chapter 2 we will discuss modern theoretical ideas on gravity and antimatter. Next, in chapter 3, we will review the particle and antiparticle gravity experiments which have been carried out. Then, in chapter 4, other gravity experiments relevant to our problem will be reviewed. Much of the material in these three chapters is not a necessary prerequisite to understanding the discussions, in chapters 5–7, of the classic arguments against "antigravity". Further, for ease of reference, we include three tables and two of our seven figures summarize many of the important experimental results.

1.2. *The arguments against "antigravity"*

Morrison's paper [Mor58b] contains the first of the three classic arguments against "antigravity", these arguments being the main focus of this paper. Later we will be discussing how, valid though these arguments may have been against "antigravity", they do not apply with similar force to modern ideas stimulated by quantum gravity. In particular, the old arguments against "antigravity" do not rule out a difference between the gravitational acceleration of antimatter and that of matter towards the earth, only a difference due to "antigravity". (See the excellent lectures by Bell [Bel87] for a comparison of the ideas of "antigravity" and modern theories of gravity.)

The Morrison argument points out that if one had "antigravity", a matter–antimatter pair on the earth's surface could be raised adiabatically to a height L with no loss of energy. Then the photonic energy obtained from the pair's annihilation would be blue-shifted in going back to the earth's surface, so that when the energy was reconverted into the pair, the pair would have acquired kinetic energy; thus energy would not be conserved. (Indeed, Morrison's argument was a variant of Wigner's perpetual motion machine [Wig49] which results from charge nonconservation.) In chapter 5 we will reevaluate the Morrison argument when applied to ideas of quantum gravity.

Shortly thereafter, Schiff looked at "antigravity" from the standpoints of the principle of equivalence and quantum field theory [Schi58, 59]. He asked whether the contribution of "antigravity" from the positrons in the vacuum polarization diagrams of atoms would have been evident in the Eötvös experiment. He came to the conclusion that the effect would have been so huge that "antigravity" could be ruled out.

However, from the viewpoint of modern field theories, the argument does not directly carry over (even though some people have that impression [Scu89; Eri90]). The two reasons that the argument does not apply to modern field theories are discussed in chapter 6. Also, as discussed in chapter 2, the fact that modern theories predict the existence of two types (of cancelling) new contributions in matter experiments means that new anomalous contributions could be masked in matter experiments.

When these facts are taken into account, even modern principle-of-equivalence experiments do not rule out a measurable anomaly in the gravitational acceleration of antimatter. (We will return to this point in chapter 8.)

The final argument was due to Good [Goo61], in a prescient article written before the discovery of *CP* violation. Good observed that if there were "antigravity", then the K_L, which is a linear combination of the K_0 and the $\bar{K}_0$, would regenerate into the K_S. This is because the K_0 and the $\bar{K}_0$ would undergo different phase shifts from the "antigravity" gravitational potential. Even from the modern viewpoint, this argument is able to rule out some theories (ignoring for now the question of assigning physical meaning to an absolute gravitational potential). However, it does not rule out all modern theories. We will discuss this argument in chapter 7.

1.3. The antiproton gravity experiment

The arguments against "antigravity" were briefly discussed in our paper which proposed doing the antiproton gravity experiment [Gold82]. A more developed version of the ideas expressed in that paper was given in the 1985 LEAR Proceedings [Gold85]. Also, in those proceedings Hynes [Hyn85] expressed the intention to perform the antiproton gravity experiment at LEAR [Hyn85; Gold86a]. The resulting collaboration [Bev86] evolved into the present experiment, which is in development [Bro86, 91; Jar87; Dye89; Holt90; Holz91]. The details of its setup will be given in section 3.2, after the Fairbank experiments are reviewed.

However, before proceeding, we wish to emphasize that this experiment is of fundamental importance [Gold88a; Pre90], apart from its use as a tool to test for new gravitational forces of the type predicted by theories of quantum gravity (see section 2.1). It would be the first test of gravity, i.e., general relativity, in the realm of antimatter. Even if the experiment finds exactly what one expects, namely that antimatter falls towards the earth just as matter does, it would be [Gold85], "A classic, one for the text books." It would be like the Pound–Rebka experiment [Pou60], the experiments testing the rotation of fermions by 4π [Rau75; Wery75; Kle76], and Aspect's test [Asp81, 82] of Bell's inequalities [Bel65, 81]. These experiments, too, found exactly what was expected, and thereby profoundly deepened our sense of understanding of fundamental physics. Of course, if a new effect were found in the antiproton gravity experiment, then there would be no telling what exciting physics could follow.

1.4. Gravity and CPT

Our ideas on gravity are really an interesting mixture of classical and quantum physics [Niet88b]. The weak equivalence principle states that the inertial mass is equal to the gravitational mass,

$$m_{\mathrm{I}} = m_{\mathrm{G}} . \tag{1.1}$$

The inertial mass is the kinematic object in Newton's law of force,

$$F = m_{\mathrm{I}} a . \tag{1.2}$$

On the other hand, the gravitational mass is the charge in Newton's law of gravitation,

$$F = -G m_{\mathrm{G}} m'_{\mathrm{G}} / r^2 . \tag{1.3}$$

Now even though the *CPT* theorem [Lüd57] tells us that the inertial mass of a particle is equal to the inertial mass of the antiparticle,

$$m_{\mathrm{I}} = \bar{m}_{\mathrm{I}} , \tag{1.4}$$

this does not imply that

$$m_{\mathrm{G}} = m_{\mathrm{I}} = \bar{m}_{\mathrm{I}} \overset{?}{=} \bar{m}_{\mathrm{G}} . \tag{1.5}$$

That is, $m_{\mathrm{G}} \neq \bar{m}_{\mathrm{G}}$ does not necessarily mean that *CPT* is broken.

Emulating Newton, we observe that if an apple falls toward the earth in a certain way, *CPT* only implies that an antiapple falls toward an antiearth in the same way. *CPT* says nothing about how an antiapple (that is to say an antiproton or a positron) falls toward an earth [Niet88c]. Thus, we see that there is nothing wrong, as a matter of quantum principle, for these new theories of quantum gravity to exhibit a violation of the principle of equivalence.

Of course *CPT* is the invariance principle upon which all modern quantum field theories are based. It implies that particles and antiparticles have equal inertial masses and lifetimes and equal and opposite charges and magnetic moments. There is *no* experimental evidence anywhere for a violation of *CPT*. All experiments yield agreement with this principle to high precision [PDG90]. For direct gravitational purposes the most important results refer to the ratios of the inertial masses of e^+/e^- and of $\bar{p}/p$. One knows that $|m(e^+) - m(e^-)| < 4 \times 10^{-8} m(e^-)$, at the 90% confidence level [Chu84], and that $|m(\bar{p}) - m(p)| < 4 \times 10^{-8} m(p)$ at one standard deviation [Gab90]. (See section 7.1 for a comment on the K_0 and $\bar{K}_0$ masses.) Interestingly, Abov et al. have looked at the possibility of obtaining a much better test from the ratio of the inertial masses of $\bar{n}/n$ by using neutron–antineutron oscillations [Abo84].

The basis of the argument that even-spin boson exchange is universally attractive is the *CPT* theorem. Thus, for *tensor* gravity to fail to be equally attractive between matter and matter and between matter and antimatter, that theorem would have to be violated. Due to its intimate connections to unitarity and the complex extension of the Lorentz group [Str64], it has generally been unthinkable to construct a *CPT*-violating theory in flat space–time.

However, in curved space–time, no generalization of the *CPT* theorem has been demonstrated, so its validity is open to question [Pen88; Ben90]. In fact, models have been proposed which predict a small *CPT* violation in curved space–time gravity [Wal80; Unw82; Ban85; Kuz85; Coh87]. A model from string theory [Kos91c], brings up the question of the mass of the graviton [GolA74].

2. Theoretical ideas on gravity and antimatter

2.1. Quantum gravity

As mentioned in the last chapter, the two great triumphs of modern theoretical physics are quantum mechanics (as finalized in quantum field theory) and classical general relativity. The unfortunate thing, however, is that at some level these two theories are incompatible. This has been emphasized especially by Wigner [Wig57, 79; Sal58], and by others [Gre68; Dav82].

The point can be understood intuitively as follows: in quantum mechanics one is taking a many-path point of view, whereas in general relativity one takes a space–time geodesic point of view. Thus, in the latter, gravitational knowledge requires precise information on position and momentum coordinates in a fashion inconsistent with the former. (For a recent example, see [Klei89], who shows that a quantum-mechanically consistent construction of gravity requires a violation of the weak principle of equivalence.)

Even though one might not be too concerned with the fundamental incompatibility of quantum mechanics and gravity, since one expects a breakdown only at the Planck scale, the problem is clear as a matter of principle. Either (i) quantum mechanics must be modified, or (ii) general relativity must be modified, or (iii) perhaps both. The point of view (i) is investigated by a quantum-cosmology community, whose work has been summarized by Hartle [Har89,90]. The point of view (ii) is taken by particle physicists in their attempt to unify all the forces of nature.

Unifying the forces of nature takes us back to the beginning of this story, where Maxwell unified electricity and magnetism [Max65a]. In modern times the weak and electromagnetic forces have successfully been combined in the electroweak theory. Attempts to unify the electroweak and strong forces have not yet been successful (the proton does not decay very rapidly, if at all). Even so, efforts have been underway for some time to quantize and unify gravity with the other forces of nature.

A generic feature of these models is that the normal spin-two graviton can have two types of new partners: a spin-one (gravivector) and a spin-zero (graviscalar). These new partners are in general massive (finite range) and have coupling strengths on the order of normal gravity which can be composition-dependent.

Many authors deserve credit for the pioneering work in this field [Lee55; Fuj71a, b; O'H72; Fer76; Sch77, 79a, b, 80; Stel78; Zac78, 79; Fei79; Fay80, 81; Oku82; Don83, 84, 85; Mac84; Gas84; Moo84; Chan85; Rob85; San86]. There have been many motivations, among them dilatation invariance, dimensional reduction, supersymmetry, and string theory. We should especially mention two investigators: Fujii's early ideas [Fuj71a, b] on a dilatation scalar were one of the motivations for the Australian mine experiments which we will discuss below. Most importantly, Scherk [Sch77, 79a, b, 80] realized the deep theoretical and experimental implications of the two partners of the graviton. Before his untimely death in 1980, Scherk discussed these ideas in terms of experimental limits on violations of the inverse-square law and the principle of equivalence (Eötvös experiments) [Sch80]. We are deeply indebted to Scherk.

In these theories, the simplest linearized classical potential between two point masses m_1 and m_2 is of the form [Mac84; Gold86c; Hug87]

$$V = -\left(\frac{Gm_1m_2}{r\gamma_1\gamma_2}\right)\left([2(u_1 \cdot u_2)^2 - 1] \mp \sum q_{\mathrm{v}1}q_{\mathrm{v}2}(u_1 \cdot u_2)\,\mathrm{e}^{-r/v} + \sum q_{\mathrm{s}1}q_{\mathrm{s}2}\,\mathrm{e}^{-r/s}\right), \tag{2.1}$$

where u_i is the four-velocity

$$u_i = \gamma_i(1, \beta_i)\,. \tag{2.2}$$

In eq. (2.1), the first term arises from normal graviton exchange. The ranges of the gravivector and graviscalar are v and s, respectively. The summation signs symbolically indicate that in principle there could be many partners of each spin, each having its own charge and range.

The vector charge per unit mass is given by q_{v}. It is expected to be composition-dependent, such as would be the case if it were baryon number or lepton number per unit atomic mass. The sign in front of the vector exchange term is critical to antimatter. It reflects the fact that the force is repulsive between like charges (matter and matter), but attractive between opposite charges (matter and antimatter).

In contrast, the force associated with scalar exchange is always attractive. This is, as noted above, always the case for even-spin exchange as in normal (tensor) gravity. The scalar charges, q_{s}, are subject to even more uncertainty than the vector charges. A very simple scalar coupling would be to the trace of the energy–momentum tensor. But the graviscalar can couple to other quantities as well, such as the square of the electromagnetic (or other gauge) field tensor(s) [Hill88; Hug89a, 90a]. In particular, it may couple to binding energies differently than to the inertial masses of elementary particles. (We discuss this in more detail in section 8.1.)

Here we want to note one "effective caveat" concerning the signs of the forces involved. The above statements are true for the *entire* force mediated by the particle exchange of a given spin. In analyzing experiments, however, one must be cautious regarding the possible absorption of the bulk of the effect of one spin exchange into the *apparent* strength of another. The minor deviations, say with variations due to differing substances, could then appear to be of either sign (see, e.g., [Pec87]). For example, suppose the average effect of a substance-dependent scalar interaction is absorbed (in the data analysis) into the tensor (Einsteinian/Newtonian) part, thus defining Newton's constant to include part of the scalar effect. The substance-dependent deviations from the average will then appear to give attractive contributions in some cases and repulsive contributions in others. What actually occurs in many experimental analyses is that Newton's constant is (implicitly) taken from (other) experiments using particular substances. Thus, substance-dependent deviations from this reference value, which includes possible vector and scalar contributions, can be either positive or negative, irrespective of whether the corrections are due entirely to vector (or entirely to scalar) interactions. This is why one must be careful to distinguish between G_{lab} and G_∞ for inverse-square law tests [Sta87a].

Taken to the static limit and assuming, for simplicity, that there is only one vector and one scalar partner of the graviton, the static potential is

$$V = -Gm_1m_2(1 \mp a\,\mathrm{e}^{-r/v} + b\,\mathrm{e}^{-r/s})/r\,, \tag{2.3}$$

where a and b represent the products of the vector and scalar charges of the two particles. The overall signs have been arranged so that both $a, b \geq 0$.

Equation (2.3) is a manifestation of another general property of field theory. If one has a charge force mediated by an integer-spin boson of mass M, then the static potential and force will be of the Yukawa form [Käl64]

$$V = -K\alpha\,\mathrm{e}^{-r/\lambda}/r\,, \tag{2.4}$$

$$F = -K\alpha(1 + r/\lambda)\,\mathrm{e}^{-r/\lambda}/r^2\,, \tag{2.5}$$

$$\lambda = \hbar/Mc\,, \tag{2.6}$$

where here we have

$$K = Gm_1m_2\,. \tag{2.7}$$

Thus, in terms of a single force, a and b represent the coupling strengths relative to G [α in eqs. (2.4), (2.5)] and v and s represent the ranges [λ in eqs. (2.4)–(2.6)]. If there were two forces approximately cancelling [Gold86b], then roughly speaking, one could have

$$|\alpha| \cong |a - b| \tag{2.8}$$

for the net effective strength. The effective range of two such approximately cancelling forces is a bit more problematic. Experimentally one only has data on the force, not on the potential. Therefore, any constant difference between the two potentials is irrelevant.

First consider a point source for the potentials. Expanding the difference of the two Yukawa potentials for $r \ll v, s$, it is straightforward to show that for an effective strength given by eq. (2.8), the apparent range, λ, may be larger or smaller than $s(\cong v)$. In fact, expanding eqs. (2.3) and (2.4) to $\mathrm{O}(r)$ for $r \ll \lambda$, and identifying coefficients, we find

$$\lambda^2 = s^2\{1 + [2(s/v - 1) + (s/v - 1)^2][a/(a - b)]\}^{-1} . \tag{2.9}$$

Since the denominator may be much larger or much smaller than 1, the effective range similarly may be much smaller or larger than $s(\cong v)$. However, it is clear that if a and b are chosen to satisfy (2.8), v and s can be chosen to satisfy (2.9). In particular, they can also be chosen to satisfy

$$\lambda \cong |v - s| . \tag{2.10}$$

Now of course two Yukawa forces do not *exactly* mimic a single force. They approximate it to some degree depending upon the error budget of the data. As we will discuss in section 4.1, a precise determination of λ is especially difficult in geophysics experiments. An experimental result roughly consistent with a single short-range force does not rule out the possibility of two opposing forces of longer ranges.

In fact, for potentials arising from integrating over distributed sources, eq. (2.10) is even easier to achieve. Consider a spherically symmetric earth of uniform density ρ. For $\lambda \ll R_{\text{earth}}$, the additional gravitational acceleration from a single Yukawa force as a function of z, the distance from the earth's surface, is [Sta87a]

$$g_{\text{Y}} \approx -2\pi G_\infty \rho\alpha\lambda(1 - e^{-z/\lambda}) \approx -2\pi G_\infty \rho z[\alpha - \alpha z/(2\lambda)] . \tag{2.11}$$

Now consider two Yukawa forces with $z \ll (v, s) \ll R_{\text{earth}}$. Compare this to a single Yukawa force with parameters

$$\alpha = b - a , \qquad \lambda = s - v \ll v, s , \tag{2.12}$$

where for definiteness we take $a > b$ and $s > v$. One gets exact analytic agreement between the right-most part of eq. (2.11) using these two Yukawa forces and the right-most part of eq. (2.11) using a single Yukawa force, with α and λ given by eq. (2.12), if

$$-\alpha/a = (\lambda/v)^2 . \tag{2.13}$$

A numerical example of this is $a = 1.00$, $b = 0.99$, $v = 100$ km and $s = 110$ km, with $\alpha = -0.01$ and $\lambda = 10$ km. What we are saying is that given an α and λ which fit the data, to some approximation one can find an a, b, v and s which also satisfy the data as well as eq. (2.12).

All of this approximately holds even in more complex mathematical calculations [Sta87b; And88a; Hug88; Niet88d] that use realistic earth models [Dzi81; Sta81b, 87b; Dah82]. In considering such calculations it is useful to note the existence of Yukawa multipole functions for the spherical-symmetric [Niet87b] and ellipsoidal-symmetric [Mas90] cases.

2.2. *Quantum gravity and antimatter*

When we originally proposed the antiproton experiment, our ideas focused on the qualitative possibility that antimatter could have a different gravitational acceleration than matter [Gold82]. By 1985, Zachos' observation [Zac78, 79], that a vector partner would produce an attraction on antiprotons and would cancel normal gravity for matter if the vector had zero mass, could no longer be avoided [Gold85].

Later it became clear to us that if one had a gravitational potential of the form of eq. (2.3), then one could have a very small effect in matter–matter interactions, and yet have a significant effect in antimatter–matter interactions [Gold86b]. This could come about if $a \cong b$ and $v \cong s$. Such a situation would be natural since it would represent an approximate symmetry between the two partners. One could imagine the differences to arise from "symmetry breaking" or, in the extreme, from higher-order gravitational corrections. Then $a - b$ and $v - s$ would be truly negligible. This demonstrates the importance of antimatter–matter experiments. They are sensitive to the orthogonal combination of couplings, $|a + b|$.

To be more specific, stimulated by reported experimental indications for inverse-square law and principle-of-equivalence violating effects with ranges on the order of 450 km or less (see chapter 4), we observed that the relative change in acceleration of the antiproton toward the earth with respect to normal g would be [Niet88d]

$$\Delta g/g \cong 0.14 a\lambda / 450\,\mathrm{km}\,. \tag{2.14}$$

However, this prediction rests on the assumption that, although small, $|a - b| \neq 0$, thus limiting the vector and scalar ranges from static (nonrelativistic) experiments that yield non-null results. There is no such constraint from static experiments if $|a - b| = 0$ to very high accuracy.

It should be noted that in quantum gravity scenarios under the static potential regime of eq. (2.3), antimatter always falls at the same rate as, or faster than, matter does towards the earth. It never falls up, as is the case with "antigravity". It never even falls slower than matter.

Also, the value of a could be large. One sees from eq. (2.1) that the various interactions have different velocity dependences. In particular, a rapidly rotating object can reach the point where the total energy becomes positive. Such a system would be unstable if the constants $a \cong b$ were too large. Using this argument with the observed stability of the 1.588 ms pulsar, only the limits

$$a \cong b \leq 70\,, \quad v, s \gg 4\,\mathrm{km} \quad \text{and} \quad a \cong b \leq 100\,, \quad v, s = 4\,\mathrm{km}\,, \tag{2.15}$$

could be obtained [Niet87a]. Lower limits could have been obtained by using the stability of the 0.508 ms pulsar reported in the direction of supernova 1987a [KriJ89]. However, this observation has been withdrawn after identification of an instrumental error [Mid90]. (Note that rotational effects in lab experiments would be too small to be observed [Niet87c].)

Of course, many others have also considered problems in this area of "non-Newtonian gravity." By definition, they are related to the question of antimatter and gravity. In the references we list some of the very interesting papers which have been recently published [Neu86; Nus86; Bars86; DeR86; Vec87; Ito87; Gas87, 88; Fuj88; Mil88; Hill88; Gin89; Halp89; Kos89a, b, 91a,b]. There are also a number of papers with direct astrophysical interest [Gla87; Pec87; Mem88; For89; Grif89; Mof89; Kos91c]. In particular, ref. [Gold91d] finds the effect of the renormalization group on the value of G at large-distance scales.

In the above paragraph, we placed the colloquially used term, non-Newtonian gravity, in quotes. This is because it is known that general relativity is non-Newtonian; i.e., the inverse-square law is violated (think of the shift of the perihelion of Mercury). Here, by "non-Newtonian," we and others mean deviations from the linearized, static limit of general relativity.

Before we discuss modern experimental tests of whether Newtonian gravity may be violated, we wish to emphasize a useful point to remember, especially when reading sections 4.2 and 4.3. The standard expectation is that quantum-gravity induced violations of Newton's inverse-square law and of the principle of equivalence will go hand in hand [Sch80]. This is so for two reasons: (i) astrophysical evidence rules out infinite-range forces of this nature (see chapter 4); (ii) further, by its very nature, the simplest vector coupling violates the principle of equivalence, as does the scalar coupling to gauge fields (see chapter 8). Even so, this expectation is not necessary. There could be a violation of one without a violation of the other. The experiments we discuss in the next two sections were all primarily designed to test for a violation of one or the other concept, not of both. There have been no long-range experimental tests of both concepts simultaneously. However, Luther is planning a torsion balance experiment which will use large masses of differing composition which will be separated by varying distances [Lut91], and so would test both concepts.

3. Particle and antiparticle gravity experiments

3.1. The Fairbank experiments

In early 1957, Fairbank attended a conference on gravity at the University of North Carolina. Fairbank had the recollection [Fai74] that DeWitt, in his summary talk, made the observation, "Nothing is known about the gravitational acceleration of antimatter." There is nothing in the conference report to this effect in the concluding session which DeWitt chaired, even though a few of DeWitt's comments concerning antimatter are given elsewhere [DeW57]. But no matter! The fire was lit.

Stimulated by DeWitt's passing observation and the Morrison–Schiff–Good arguments, Fairbank and his student Witteborn began a program to compare the gravitational acceleration of electrons and positrons [Wit67]. The method chosen was to analyze the time-of-flight distributions of electrons that were freely falling inside a vertical metal drift tube. The tube was constructed so that stray electric and magnetic field gradients were reduced to less than 10^{-11} V/m. This was necessary since the force of gravity is so small,

$$m_e g/e = 5.6 \times 10^{-11}\ \mathrm{V/m}\,, \tag{3.1}$$

for electrons. This method could also be used to measure gravity on ions [Wit65].

There were many questions of principle surrounding this experiment that remain pertinent to this day [Bro86, 91; Jar87; Dye89; Dar90]. To begin with, there is the Schiff–Barnhill (SB) effect [Schi66]. As the experiment was in preparation, Schiff and Barnhill observed that the electrons inside the metal of the drift tube would sag under gravity, until the gravitational force was balanced by the electrostatic force of compression. This would create an electric field inside the drift tube that would exactly cancel the acceleration due to gravity on the electron. In fact, if M, Q and m_e, e are the mass and charge of the particle being measured and of the electron, respectively, then the effective gravitational acceleration that should be measured is

$$g_{\mathrm{eff}} = g[1 - (m_e Q/Me)]\,. \tag{3.2}$$

Thus, for the electron one should measure zero, and indeed Witteborn and Fairbank found [Wit67] that $g_{\mathrm{eff}} < 0.09g$. However, later, two other main questions of principle concerning the experiment were raised. (See [Dar90] and [Ros89] for a review and resource letter, respectively, on the questions we now discuss.)

3.1.1. Ionic versus electronic sag

The first question of principle about the Fairbank experiment was raised by Dessler, Michel, Rorschach and Trammel (DMRT). They observed that not only the electrons but also the ions should sag in the drift tube [Dess68; Her68]. From the equation analogous to (3.2), this would produce an effect 2000 times greater and of opposite sign. Indeed, early experiments using centrifugal [Bea68] and compressional [Cra69] potentials seemed to vindicate [Bea68; Cra69; Schi70] these predictions [Dess68; Her68]. However, Lockhart, Witteborn and Fairbank [Loc77, 88] suspected that the ion-sag potential might have been shielded at low temperatures in their drift tube. When they performed an experiment to test this, they found an ambient field of order 3×10^{-7} V/m above 4.5 K, whereas below this temperature the ambient field rapidly dropped, to a magnitude consistent with the SB prediction of -5.6×10^{-11} V/m.

Obviously there has been considerable disagreement as to the sign and size of the gravitationally induced electric field through solids (SB, DMRT), and even as to understanding why Lockhart et al. [Loc77, 88] did not observe higher fields at room temperature. However, we suggest that perhaps the essential features can be described as follows. This would yield the conclusion that both SB and DMRT effects occur, but that under different circumstances one or the other dominates [Gold91b].

In terms of induced electric fields, the effect of differential compression as a function of height through a solid is negligible for non-piezo-electric materials. However, in an insulator, the much larger gravitational force on the ions will cause them to sag farther than the electrons, so that the induced stabilizing electric field should be of the DMRT sign and size ($E \sim -M_{\text{ion}} g/e$).

The above effect is reduced only to the extent that the localizing forces (in the absence of gravity) are similar for ions and for electrons. But in a perfect conductor, this last does not transpire, since the conduction-band electrons experience no localizing force at all. Thus, the ionic response is overwhelmed by the much larger motion of the electrons, and the SB field ($E = +m_{\text{e}} g/e$) results overall.

A perfect conductor is an ordinary conducting material at zero temperature, or a superconductor below its critical temperature. What happens in an ordinary conductor at finite temperature? Think of an essentially free (Fermi) gas of (conduction) electrons at zero temperature in a gravitational field. They tend to fall to the bottom of the solid they are in, but the Fermi pressure resists this, allowing only small subsidence. Thus, macroscopic charge separation is not an issue. However, the subsidence can easily be large enough to screen the electric field due to the ionic sag.

Now heat the electron gas to finite temperature. The conduction electrons are excited by thermal fluctuations (phonons). This increases the pressure opposing the gravitationally induced compression. The average height by which the conduction electrons are raised is of order kT/mg, due to equilibration of the gravitational and thermal (kinetic) energies. Although the electrons are not localized in the usual sense, the thermal fluctuations reduce the fall of the electrons under the force of gravity. Once again, the larger gravitational force on the ions can induce a larger motion than that for the electrons and DMRT results.

Therefore, there may be a (material-dependent) temperature at which an order of 10^4 (i.e., $\sim M_{\text{ion}}/m_{\text{e}}$) times larger gravitational force on the ions is compensated for by an order of 10^{-4} relative reduction in the strength of the electron-localizing forces. At that temperature, T_0, the gravitationally induced electric field would vanish, because the electron sag cancels the ion sag. Below T_0, the field would grow to the SB strength as the temperature is lowered further.

3.1.2. The patch effect

The second question of principle concerning the Fairbank experiment concerned the "patch effect". (Fields that are produced from irregularities in the surface and crystalline structure of a conductor are called the "patch effect".) In principle, patch-effect fields can be even larger than ion-sag fields and so could have been devastating to the Fairbank experiment [Wit77]. The low field that Witteborn and Fairbank measured suggested that the stray fields from this second source were also being shielded at low temperatures. Understanding this shielding has been a subject of theoretical investigation, and is not totally understood to this day [Huts78; Han78; Bar88]. The patch effect itself remains a subject of vigorous experimental investigation [Dar89].

Witteborn and Fairbank hoped to go on and measure the gravitational acceleration of positrons. From eq. (3.2) they would have expected to find $g_{\mathrm{eff}} = 2g$ [Wit67]. However, they were not successful because the technology of that era was not advanced enough to produce the necessary supply of low-energy positrons. Even so, there is a folklore extant [Eri90] which perpetuates the erroneous belief that in their 1967 paper Witteborn and Fairbank reported the measurement of the gravitational acceleration of the positron.

In recent years Fairbank returned to the positron problem. With the modern positron sources and cooling techniques now available, he was reconsidering a measurement of the gravitational acceleration of the positron [Fai88a]. This experiment would have been complementary to the antiproton gravity experiment [Gold87]. As such, it was equally worthy of support. Fairbank's death in 1989 prevented this goal from being reached.

3.2. The antiproton gravity experiment

The antiproton gravity experiment owes much to the work of Fairbank [Gold82]. As presently being developed, the experiment will work as follows [Bro86, 91; Jar87; Dye89; Holt90; Holz91]. A 2 MeV beam from LEAR, containing $\sim 10^9$ antiprotons in a 250 ns bunch, will be directed towards a degrading foil (see fig. 1). The foil will be at the entrance to an electromagnetic, Penning-style "catching" trap. This trap will be approximately 50 cm in length. The degraded beam will be allowed into the trap while it has a voltage of 50 kV at the endcap opposite the entrance. About 10^8 antiprotons will be captured in the trap by pulsing the voltage on the entrance cap from ground up to 50 kV before the antiprotons return back out the entrance. Electron cooling will then bring the antiprotons to room temperature.

After transferring the antiprotons to a smaller Penning-style trap, the antiprotons will be cooled to a few K by resistive cooling. After (possible) transfer to a third "launching" trap, the voltage holding the antiprotons in the trap will be lowered, allowing approximately 100 particles at a time to be released into a vertical drift tube. This drift tube of approximately 50–100 cm in length, will shield the antiprotons against stray electric fields and will have a surface designed to reduce the patch effect. The drift tube will be surrounded by a superconducting magnet which will produce a guide field. The field will be uniform to better than a part in 10^5, so that the force on the antiproton due to the interaction of a magnetic field gradient on the effective magnetic moment of the antiproton will be small compared to the force of gravity.

Conceptually, the actual gravity measurement will be done as follows. The antiprotons will be released by dropping the voltage in the trap endcaps at time $t = 0$. With some distribution of energies, the antiprotons heading up will go into the drift tube. Those with large kinetic energy will quickly race through the drift tube of effective length L and be detected at the top of the tube, perhaps by a microchannel plate with attendant fast acceleration at the end of the drift tube. As time goes on, the antiprotons with smaller and smaller initial kinetic energy will arrive. Finally, the last antiproton with just enough energy to make it up the drift tube against the force of gravity will arrive at time $t = \tau$. The

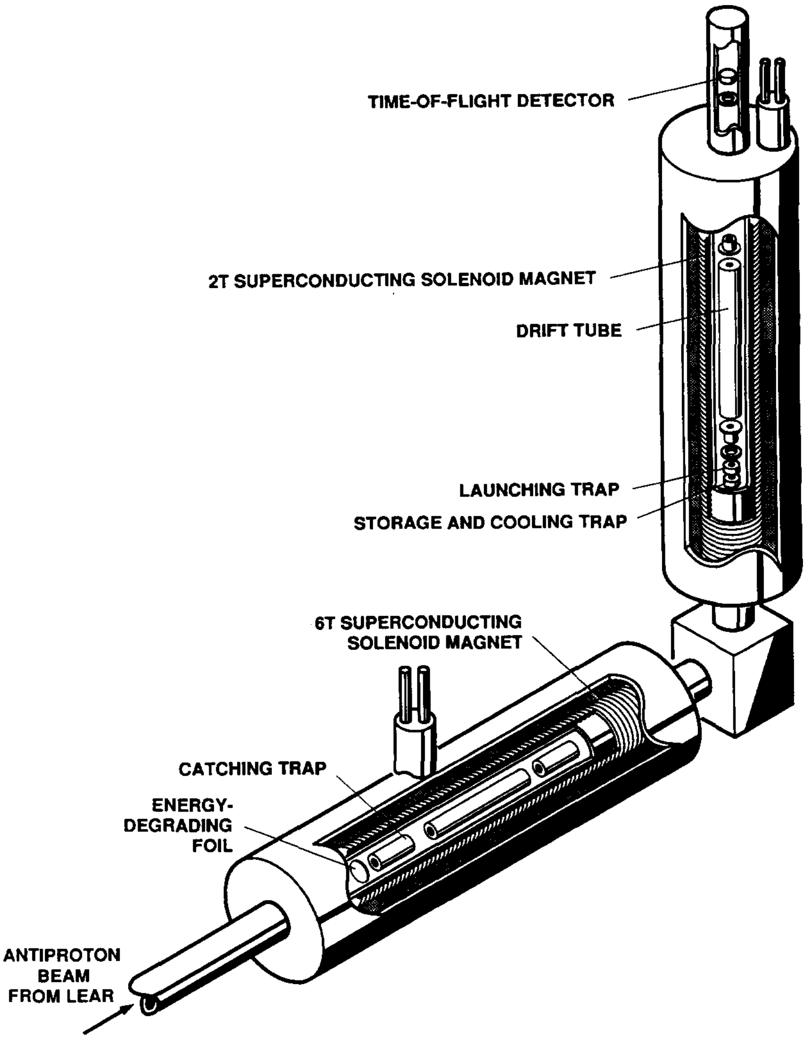

Fig. 1. Schematic diagram of the antiproton gravity experiment. Taken, with modification, from [Dye89].

value of the gravitational acceleration on the antiproton is then given by

$$\tau = [2L/g(\bar{\mathrm{p}})]^{1/2} = 0.452\,\mathrm{s}(L/\mathrm{m})^{1/2}[g(\mathrm{p})/g(\bar{\mathrm{p}})]^{1/2}\,, \tag{3.3}$$

where L is the effective length of the drift tube. Launched 100 at a time, to reduce the mutual Coulomb forces among them, the antiprotons will eventually build up a time-of-flight spectrum. The end point of this spectrum will yield the value of $g(\bar{\mathrm{p}})$.

H^- ions have the same inertial mass (to a part in a thousand), the same charge, and in this specific experiment almost the same effective magnetic moment as the antiproton. Therefore, the experiment will use negative hydrogen ions as a calibration [Holz 88], thereby cancelling systematic effects, and thus affording a precise measurement of the ratio $g(\bar{\mathrm{p}})/g(\mathrm{H}^-)$. Protons will also be used. Preliminary experiments will measure gravity on xenon and lower mass ions.

3.3. Other antimatter gravity experiments

There have been many interesting ideas to perform other antimatter gravity experiments. However, because they need a supply of antiparticles, antimatter gravity measurements are tied to the general physics programs which are possible with the advent of intense, low-energy, antiparticle sources [Bonn88; Ead90].

A number of investigators [Ead89; Haj89] have proposed using the "gravitational magnetron effect" on the antiproton [Ead89]. As is well known [CheF84], the cyclotron orbit of a particle with charge q falling vertically under gravity in a magnetic field parallel to the earth's surface will experience an additional force given by $\boldsymbol{g} \times \boldsymbol{B}$, and constant magnitude of velocity $v = mg/qB$. This drift would be a measure of gravity on the antiproton. Of course there are major shielding problems just as with the antiproton gravity experiment.

An idea of how difficult shielding problems will be for any experiment, including the above, can be obtained by noting the results of Reiner and collaborators [Rei85, 86]. They looked for a long-range force which would affect the orbit of the Tevatron proton beam. The limit they obtained for the coupling constant of such a new force was $\kappa \leq 10^{19} G$. Therefore, to obtain a result to 1 part in 100, any experiment must improve on this particular free-space experiment by twenty-one orders of magnitude, eliminating stray electromagnetic fields to this level.

The possibility has also been raised of using ion-trap techniques, such as those employed to measure and compare the inertial masses and magnetic moments of the electron and positron and the proton and antiproton, to look for violations of the principle of equivalence [Wid88; Gas89; Hug91]. It can be argued that, by observing anomalous frequency shifts of the radiation emitted from the traps, one is seeing an anomalous redshift caused by non-Einsteinian forces instead of a violation of *CPT*. As an example, an anomalous long-range tensor interaction has been discussed [Hug91]. Even granting that this interesting interpretation is not based on a quantum field theory, predicted redshifts depend critically on the types of new interactions that exist, as we will come to in section 8.1. For the types of new gravitational forces we are mainly considering, the effect would be small.

Kalogeropoulos and his collaborators have long been interested in using an antineutron beam time-of-flight technique for an experiment analogous to the falling neutron-beam experiments described in section 3.4 below. Unfortunately, it has not yet been possible to obtain both low-energy and well-defined beams of antineutrons. They are produced at high energy and any attempt to cool them or diffract them is frought with annihilation difficulties [Bran81].

Several methods have been proposed to produce antihydrogen atoms. Three specific proposals are given in [Pot86; Deu86, 88; Gab88a]. (See [Ric87], [Neum87] and [Mit88] for reviews.) After it has been proven possible to make antihydrogen, it then may be possible to find a way to laser-cool and store antihydrogen in a magnetic trap. This would possibly allow a measurement of gravity on antihydrogen that would avoid the sensitivity to stray electric fields [Gab88b; Niet88b].

Finally, we observe that one antimatter experiment "has been done" on a galactic distance scale, using the neutrinos from supernova 1987a. LoSecco pointed out that the neutrinos, which arrived in a 12 s interval, have been identified as being both neutrinos and antineutrinos. Since the principle of equivalence predicts a time delay of one to six months from traversing our galactic gravitational field (see [LonM88; Krau88] and section 4.4), this meant the time delays of these particles and antiparticles were equal to an accuracy of (0.77–4.6) parts per million [LoS88]. (Their post-Newtonian parameters γ [Mis73; Wil84] were equal to $|\gamma(\nu_e) - \gamma(\bar{\nu}_e)| \leq (1.5\text{–}10) \times 10^{-6}$.) Unfortunately, this puts no constraints on non-Newtonian gravitational forces with ranges $\ll 1$ pc.

3.4. Laboratory tests of gravity on neutrons and photons

To this day, the Witteborn–Fairbank experiment [Wit67] remains the only measurement of gravity on an elementary charged particle. The antiproton gravity experiment, and its attendant measurement of gravity on the proton, would be the next.

However, for a number of years now there have been measurements on the neutron. The first done was by McReynolds [McR51]. A narrow beam of thermal neutrons was defined by slits and detected after traveling 12 m horizontally from the slits. Its position at detection was compared to that of a similar beam which had been sent through a 25 cm filter of BeO and was detected at a lower position. The drop of the second beam yields a measure of local g,

$$g = 935 \pm 70\ \mathrm{cm/s^2}\,. \tag{3.4}$$

Somewhat later, Dabbs et al. [Dab65] improved on this result by using a 180 m flight path for particularly slow neutrons. The velocities were determined by diffraction from $\langle 100\rangle$ and $\langle 002\rangle$ lattice spacings of a polycrystalline beryllium filter. The resultant fall of the two slow beams with respect to the fast beam (12.7 and 15.5 cm) gave the values

$$g(100) = 975.4 \pm 3.0\ \mathrm{cm/s^2}\,, \qquad g(002) = 973.1 \pm 7.0\ \mathrm{cm/s^2}\,, \tag{3.5}$$

to be compared with the local value at Oak Ridge, $g = 979.74\ \mathrm{cm/s^2}$.

Here one should mention the classic COW [Col75] experiment, which showed that classical gravity can act as a potential in a quantum-mechanical system. In this experiment a beam of individual, slow neutrons was sent through a single-crystal interferometer. An individual neutron would be half reflected and half transmitted through the first reflector. So, one half of the wave function would go to one side and one half to the other side of the interferometer. However, the interferometer could be rotated on an axis parallel to the beam. This means that if the interferometer plane were to be rotated away from being parallel to the earth's surface, half of the beam would be at a higher gravitational potential than the other half. This would cause a phase shift of this higher beam, i.e., the horizontal beam further away from the earth's surface, with respect to the lower horizontal beam. The interference pattern obtained by recombining the two beams would be a functional measure of local gravity (G in terms of g) *and* Planck's constant combined [see eq. (3.7) below].

The dependence of the relative phase β on the rotation angle ϕ is

$$\beta = q_{\mathrm{grav}} \sin\phi\,, \tag{3.6}$$

$$q_{\mathrm{grav}} = 4\pi\lambda g(m/h)^2 d(d + a\cos\theta)\tan\theta = 59.6^\circ\,, \tag{3.7}$$

where $\lambda = 1.445$ Å is the neutron wavelength, g is local gravity, h is Planck's constant, m is the neutron mass, θ is the Bragg angle 22.1°, and a and d are dimensions of the crystal. The authors of [Col75] experimentally found the value

$$q_{\mathrm{grav}} = 54.3^\circ - q_{\mathrm{bend}}\,, \tag{3.8}$$

where q_{bend} was up to that time an unmeasured systematic due to the bending of the crystal. This bending angle was expected to be a few degrees, so the difference between eqs. (3.7) and (3.8) was presumed to be due to the sag of the crystal. Later experiments measured the bending angle with X-rays and verified the results to even higher precision [Stau80].

Recently, using the results of this experiment, a bound $|a|\lambda^2 < 1.41\,\mathrm{km}^2$ was obtained for a new gravitational force [Bert86]. See the reviews by Greenberger and Overhauser [Gre79, 83] and Werner and Klein [Wer86] for detailed information on this field.

The principle of equivalence for neutrons has been measured with increasing accuracy [Sea82; Schm89] using the method of Koester [Koe67]. In this method the values of neutron scattering lengths on a particular substance with and without significant gravitational interactions are compared. Specifically, a neutron gravity refractometer is used to obtain the effective scattering length with gravity, b_{eff}, and standard measurements yield the standard scattering length b. In a gravity refractometer, a horizontal beam of neutrons is allowed to fall from a height onto a liquid mirror of number density n. The critical height for total reflection, h_0, can be shown to satisfy [Sea82]

$$M_{\mathrm{G}} g h_0 = V_0 = 2\pi\hbar^2 n b_{\mathrm{eff}}/M_{\mathrm{I}}\,, \tag{3.9}$$

where M_{G} and M_{I} are the neutron's gravitational and inertial masses, V_0 is the optical potential and b_{eff} is the effective scattering length. One then obtains the quantity [Schm89]

$$\gamma = b_{\mathrm{eff}}/b = (M_{\mathrm{G}}/M_{\mathrm{I}})(g_{\mathrm{n}}/g) = 1.00038 \pm 0.00025\,. \tag{3.10}$$

where g_{n} is the gravitational acceleration of neutrons compared to bulk matter g. Measuring gravity on photons comes in the guise of redshift experiments. It is interesting to recall that soon after Morrison's paper [Mor58b] was published, a disagreement between Schiff [Schi60] and Dicke [Dic60] appeared in the literature, with Dicke arguing strongly that it was important to perform redshift experiments because the Eötvös experiment did not rule out an anomalous redshift.

The "weight of photons" was obtained in the Pound–Rebka experiment [Pou60,65]. Pound and Rebka used the 14.4 keV iron Mössbauer line in iron as a source. For the photons to be reabsorbed after they had dropped a distance h (75 feet), the prediction is that the source must be moving at a

Table 1
Some particle and antiparticle gravity experiments, listed in chronological order

Experiment	Results
14.4 keV iron Mössbauer photons fall distance h in the earth's gravitational field. They are reabsorbed by a source with velocity v_0 [Pou60, 65].	$v_0/(2gh/c) = 0.9990 \pm 0.076$.
Fall of a well-defined, diffracted beam of thermal neutrons in the earth's gravitational field [Dab65].	$g_{\mathrm{n}} = (975.4 \pm 3.0)\,\mathrm{cm/s^2}$.
Time of flight of slow electrons up a drift tube [Wit67]	$g_{\mathrm{e}} - g_{\mathrm{e\text{-}sag}} < 0.09\mathrm{g}$, where $g_{\mathrm{e\text{-}sag}}$ was expected to be g, from the Schiff–Barnhill effect [Schi66].
Equality of arrival times of neutrinos and antineutrinos from supernova 1987a, after being time-delayed by our galactic field [LoS88].	Time-delays equal to accuracy of $(0.77\text{–}4.6) \times 10^{-6}$. Post-Newtonian parameters γ equal to $\lvert\gamma(\nu_{\mathrm{e}}) - \gamma(\bar{\nu}_{\mathrm{e}})\rvert \leq (1.5\text{–}10) \times 10^{-6}$.
Neutron gravity refractometer is used to obtain scattering lengths [Schm89].	$g_{\mathrm{n}} = (1.00038 \pm 0.00025)(M_{\mathrm{I}}/M_{\mathrm{G}})g$, where M is the mass of the earth.

velocity

$$v_0 = 2gh/c = 4.905 \times 10^{-15}c \,, \tag{3.11}$$

for observations at the upper and lower stations to be identical. The final results of the series of experiments [Pou65] gave a result of

$$v_0/(2gh/c) = 0.9990 \pm 0.0076 \,. \tag{3.12}$$

The related redshift experiments using spacecraft will be discussed in section 4.4.

In table 1 we list some of the important results from particle and antiparticle gravity experiments that we have discussed in this chapter.

4. Other experiments relevant to antimatter gravity

4.1. Airy experiments

Since geophysical considerations have had such an important impact upon this field, we begin this chapter with a discussion of "Airy experiments." Beginning in 1826, and concluding after a long break in 1856, Airy set out to determine the "average density of the earth" by making gravitational measurements both at the top and bottom of a mine shaft, ultimately at the Harton mine [Air56a, b]. As has been emphasized by Clotfelter [Clo87], early experiments in gravity (such as that by Cavendish [Cav98]) did not try to determine "Newton's constant," as we call it. Rather, the mean density of the earth was obtained because, starting with Newton, ratios or proportionalities were used. In fact, the first well-known paper with "constant" in the title was published in 1873 [Cor73], the year the dyne as a unit of force was defined [Clo87]. (See [Poy94] and [Bul75] for historical reviews of this early research.)

To see the connection between the density of the earth and Newton's constant points of view, let us start by considering gravity within and outside a spherically layered earth. At any point, the gravitational acceleration at a distance r from the center of the earth is

$$g(r) = Gm(r)/r^2 \,, \tag{4.1}$$

where we have used here the geophysics convention that gravity is positive downwards. $m(r)$ is the mass located within the radius r and is

$$m(r) = 4\pi \int_0^r \rho(r')r'^2 \, \mathrm{d}r' \,, \tag{4.2}$$

$\rho(r)$ being the local density.

Airy used a pendulum to measure local g at the top ($r = R + d$) and bottom ($r = R$) of the shaft at Harton. To good approximation, Airy could take R to be the radius of the earth and, because of the inverse-square law, could take all the material within R to be at the average density of the earth, ρ_e. Then to first order in (d/R), the normalized difference of the gravity measurements was given by

[Air56a]

$$[g(R+d)-g(R)]/g(R)=(d/R)[-2+3(\rho_s/\rho_e)]\,, \tag{4.3}$$

where ρ_s is the density of the rock near the surface. Airy found a high value, $\rho_e = 6.565\ \mathrm{g/cm^3}$ [Air56b], compared to the now accepted value of $5.515\ \mathrm{g/cm^3}$ [Dzi81].

To relate this to the standard modern discussion, take the derivative of eq. (4.1). This leads to relations for the gravity gradient

$$\mathrm{d}g(r)/\mathrm{d}r = -2g(r)/r + 4\pi G\rho(r)\,, \tag{4.4}$$

or

$$\mathrm{d}g(r)/\mathrm{d}r = 4\pi G[-(2/3)\bar{\rho}(r)+\rho(r)]\,. \tag{4.5}$$

$\bar{\rho}(r)$ is the average density within the radius r,

$$\bar{\rho}(r) = m(r)/\tfrac{4}{3}\pi r^3\,, \tag{4.6}$$

so that $\bar{\rho}(R)=\rho_e$. The first term in eq. (4.4) is called the free-air gradient. The second term is called the double Bouguer correction, and it is effectively zero when one traverses air. [Observe that for a uniform earth, Airy's relation (4.3) is a difference form of eq. (4.5).]

It is eq. (4.4) that is useful in analyzing modern-day Airy experiments. It also illustrates an important difference in principle between Airy experiments and tower experiments [Zum90]. An Airy experiment is really a large-scale Cavendish experiment and directly yields G since the mass of the attracting material is explicitly taken into account in the last term of eq. (4.4). However, a tower experiment can only obtain information on $G(r)$ with input of G_{lab} and of an explicit new force law (such as a Yukawa law). This is because, like a satellite, a tower experiment measures gravity outside all of the mass, and so is always measuring the product GM (in the form of g) for Newtonian gravity. Although an Airy experiment may well use G_{lab} in its analysis, in principle it does not have to.

If one generalizes eq. (4.4) to include Yukawa forces of the form of eqs. (2.4)–(2.7), then one finds that the anomalous (non-Newtonian) gravity gradient is proportional to α but, because of its Yukawa nature, a slowly-varying function of λ. (For more details on this point see section IVB of [Sta87a] and also [Hug89b].) Therefore, it is easier for Airy experiments to place good bounds on the relative coupling constants of new gravitational forces than on possible scale lengths of these forces.

It is also interesting to consider the form of eq. (4.5). This shows us that if one is going down through the earth, gravity will continue to increase until the local density becomes larger than two-thirds the average density inside it. That is why gravity continues to increase going down, near the earth's surface, where ρ_s is about $2.7\ \mathrm{g/cm^3}$. The loss of the effect of the mass left overhead cannot compete with the effect of getting closer to the center of earth. Of course, that changes when the local density grows large enough compared to the average interior density.

If one calculates gravity in the earth's interior taking $\rho(r)$ from the Preliminary Reference Earth Model (PREM), which is the most widely accepted theoretical model of the real earth [Dzi81], one finds that the gravity gradient changes sign three times within the earth. (See table G.2 of [Sta77] for a demonstration of this observation based on an earlier earth model.) In fig. 2 we plot $g(r)$, $\rho(r)$, and

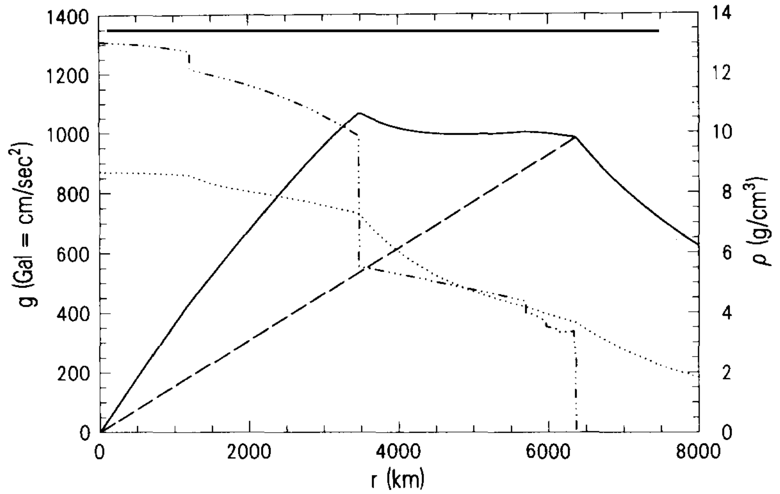

Fig. 2. Using the PREM model of the earth [Dzi81], we plot as a function of the radius, r, from the center of the earth the following quantities: the local gravity $g(r)$ (solid line), the density $\rho(r)$ (dash-dotted line), and two-thirds the average density, $\frac{2}{3}\bar{\rho}(r)$, within r (dotted line). The dashed line shows what $g(r)$ would be if the earth were of uniform density.

$\frac{2}{3}\bar{\rho}(r)$. It is amusing to verify the change of sign of the gradient of $g(r)$ as the curves for $\rho(r)$ and $\frac{2}{3}\bar{\rho}(r)$ cross each other.

4.2. *Tests of the inverse-square law*

Even in the late 1970's, there were surprising gaps in our knowledge of how precisely static gravity can be described in terms of the Newtonian form. At the planetary distance scale, Newtonian gravity was known to be accurate. The inverse-square law had been tested by the planets themselves and by spacecraft. In the laboratory, inverse-square law experiments were relatively imprecise. Even worse, on intermediate scales *nothing* was known.

Motivated by this lack of knowledge, Long undertook an inverse-square law experiment on the scale of 4–30 cm [Lon74]. The experiment measured the attraction of a ball to different-sized rings. Long [Lon76] reported a violation of Newton's law, with the parametrization

$$G(r) = G_0[1 + (2.0 \pm 0.4) \times 10^{-3} \ln(r/1\,\mathrm{cm})] . \tag{4.7}$$

(Consult [Gil87,90] for exhaustive bibliographies of measurements on Newtonian gravitation and see [Wor82; Wil84, 90b] for general bibliographies on gravitation. A non-Newtonian gravity supplement to ref. [Gil87] is in preparation [Fis91].)

Long tried to explain this result in terms of a new gravitational interaction somehow analogous to the vacuum polarization of electromagnetism, but with the wrong sign [Lon80]. This would have been an "antigravity" type of phenomenon. Indeed, it is noteworthy that such a system (letting $\alpha_{\mathrm{em}} \rightarrow -\alpha_{\mathrm{em}}$) was used by Dyson [Dys52] to show that the Feynman perturbation series in QED has zero radius of convergence.

However, when Spero et al. (R. Newman's group) performed an experiment using a test mass suspended from a torsion balance to probe the gravitational field inside a mass tube, they found no violation on this scale [Sper80]. Indeed, in this paper Spero et al. invented the α–λ plot used to define allowed and disallowed parameter space for a single Yukawa force. Their work indicated that for $\lambda = 1$ cm, 1 m there are limits $|\alpha| < 10^{-3}$, 10^{-1}, respectively. (Other tests for non-Newtonian gravity on laboratory scales include [Pan79; Cha82; CheY84; Mily85; Kur85; Hos85; Mio87; Spe87].)

But Long's work also stimulated others to look more closely at the whole question of experimental tests of Newtonian gravity. This started with the excellent discussion of Mikkelsen and Newman [Mik77]. Gibbons and Whiting [Gib81] and Hut [Hut81] continued the discussion in terms of new gravitational forces from quantum gravity.

Indeed, the above results of [Lon74] and [Mik77] helped inspire experiments on the scale of tens of meters. These experiments are especially entertaining as they have involved the movement of large quantities of liquid. The first experiment compared the gravitational attractions of an empty and full, large oil tank [Yu79]. Although this experiment only verified the constancy of G to 10% for $\lambda \sim 10$ m, it was a precursor to later experiments.

The use of changing lake elevations was pioneered by the Australian group [Moor88]. At the Splityard Creek reservoir in Queensland, variations of up to 10 m per day occur in a hydroelectric reservoir used for peak-power storage. By measuring the change in local gravity acceleration from a tower in the middle of the reservoir as the water rose and fell, Moore et al. found $G = (6.689 \pm 0.057) \times 10^{-11}\ \mathrm{m^3\ kg^{-1}\ s^{-2}}$, at an effective range of 22 m [Moor88]. This agrees with the accepted result of eq. (4.8) below to within one standard deviation. A similar result was found by Müller et al. in Germany [Mül89]. For effective ranges of 40–70 m, they quoted a measured deviation of G from the laboratory value of $(0.25 \pm 0.40)\%$.

On longer scales (of the order of hundreds of meters), the work of Stacey, Tuck and collaborators was seminal [Sta78, 81, 83, 87a, b; Hol84, 86]. As mentioned previously, in 1971 Fujii had predicted a new scalar force with a range of ~200 m and a coupling $\alpha = 1/3$ [Fuj71a, b]. Stacey and collaborators felt that an Airy experiment down a mine shaft could rule out such an effect. Using the Mt. Isa and Hilton mines in Australia, they measured gravity to depths of nearly 1 km and easily ruled out the Fujii idea. However, they had a small effect left over; it represented a new repulsive force with $\alpha \sim -0.01$ and λ on the order of a few hundred meters. From eqs. (2.3)–(2.7) this meant that the Australian experiment found $G_\infty = G$ to be about 1% less than the value measured in the lab by Luther [Lut82],

$$G_{\mathrm{lab}} = (6.6726 \pm 0.0005) \times 10^{-11}\ \mathrm{m^3\ s^{-2}\ kg^{-1}}\,, \tag{4.8}$$

$$G_{\mathrm{lab}} \cong G_\infty(1 - a + b)\,. \tag{4.9}$$

(We refer the reader elsewhere for discussions on the possibility that G varies with time [Wes80; Van81; Hel83; Wu86; Liu90; Dam90; Nor90].)

Stacey also conceived the idea of an Airy experiment in an ocean [Sta78,83]. This concept was taken up Ander, Hildebrand, Zumberge and collaborators, and led to proposals to perform experiments in the Pacific Ocean, the Greenland icecap, and the Antarctic icecap. Of the three, the first to "get off the ground" was the Greenland experiment, which obtained funding in 1985. The Greenland experiment was performed in the summer of 1987 [Chav87], at the 2 km borehole at Dye-3. It yielded unexplained gravity residuals [And89a,b; Zum90] which a priori could have been taken as evidence for a new attractive force with $\alpha \sim 0.024$–0.035 for $\lambda \sim 5.4$ km–225 m [Niet89b].

However, there was one important caveat. Since any finite number of measurements can be duplicated by some mass distribution and Newtonian gravity, the collaboration performed an "ideal body analysis" on the bedrock under the ice sheet to see if a reasonable geology could mimic the measured residuals. This analysis [Par74, 75; And87] can be thought of as appropriately placing the least amount of excess matter (rock of different density) in the bedrock so as to model the residuals by Newtonian gravity. It was found that an unexpectedly large but not geologically unreasonable amount of high-density rock could do this [And89a, b; Zum90] for the Greenland signal.

Of course, it was realized [Par89] that an ideal body solution can be a problem for any experiment which measures gravity along a horizontal plane and a vertical line. The ideal body analysis would have much more difficulty mimicking a true non-Newtonian force by Newtonian gravity if gravity were measured on parallel horizontal planes.

With hindsight, this is a manifestation that Gauss' law is a more restrictive test of Newtonian gravity if one measures the flux going through two (or more) parallel surfaces rather than the flux going through one horizontal surface and along a vertical line. In midstream the ocean experiment [Hil88], which began taking data in 1988, changed its plan of attack. Gravity would be measured on planes on the ocean surface, the sea bottom, and at depth in the ocean. At this writing, the data taking is complete and analysis is well underway.

Prior to the Greenland announcement, Eckhardt et al. [Eck88; Rom89] reported a violation of the inverse-square law from gravity observations taken up the 600 m WTVD tower in North Carolina. For a single Yukawa force, the observations corresponded to an attractive force with parameters ($\alpha \sim 0.0204$, $\lambda \sim 311$ m). This experiment and the Australian mine experiment were found to be consistent if there are two (approximately cancelling) new forces with ranges on the order of 100 m [Eck88; Sta88; Moor88; Rom89].

However, Bartlett and Tew [Bart89a, b, c, 90] pointed out that the observations made by field geophysicists are not distributed randomly on the surface of the earth. They tend to follow roads and low ground, avoiding marshes and the sides of mountains. Therefore, Bartlett and Tew questioned whether the observed inverse-square law violations are devoid of systematic errors due to such biases. Upon checking this, the North Carolina result became consistent with a null result [Jek89, 90].

It should be noted that the Australian program [Sta81a,b, 87a] was also stimulated by older reports of anomalies in mine, borehole and ocean data. Similar anomalies have also been reported more recently [Hsu87; Thom88, 90]. Considerations similar to those of Bartlett and Tew [Bart89a, b, c, 90] and Parker and Zumberge [Par89] may well be the explanations of these anomalies.

The Australian mine collaboration is in the midst of calculating the effects caused by the regional gravity survey avoiding the sides of mountains. The first effect, that due to the raw terrain correction, reduces their reported anomaly by approximately 90%. However, a remaining correction to the gravity measurements remains to be calculated, so that the final result is still unknown [Tuc89; Sta89].

Two other tower experiments have reported null results. Thomas et al. [Thom89] performed an experiment up the 465 m BREN tower at the Nevada test site. Between the top and bottom of the tower, their gravity readings as a function of height deviated systematically from the Newtonian expectation. However, the magnitude of this deviation was consistent with their experimental error and was small compared to the effect suggested by the original analysis of the WTVD tower experiment [Eck88; Rom89]. At the top of the tower the anomaly was -60 ± 95 μGal ($1\ \mathrm{Gal} = 1\ \mathrm{cm/s^2}$) with respect to the bottom. The University of Colorado group observed no effect from measurements up the 300 m NOAA weather tower in Erie, Colorado. They found a maximum offset up the tower of 21 ± 27 μGal [Spe90; Cru91]. This roughly corresponds to limits of $|\alpha| \leq 10^{-2}$ and $\leq 10^{-3}$ for $\lambda = 10$ m and ≥ 100 m, respectively. In fig. 3, modified from [Spe90], we show bounds on Yukawa violations of the inverse-square law that come from four different experiments.

Other experiments have also been proposed.

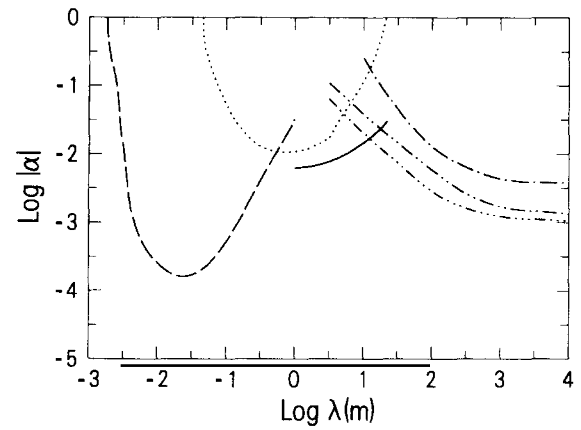

Fig. 3. Limits on violations of the inverse-square law due to a single Yukawa force obtained from a number of null experiments. Plotted are upper bounds on the strength $|\alpha|$ as a function of range, λ. Modified from the analysis of [Spe90] and at the 1σ level, the long-dash and dotted curves are the laboratory experiments of [Hos85] and [Pan79], respectively. Similarly, the dash–(single, double and triple)-dotted curves are the tower experiments of [Thom89], [Jek90] and [Spe90], respectively. Finally, the solid curve shows the limit from the Australian lake experiment as reported in [Sta87a; Moor88].

Table 2
Some tests of the inverse-square law, listed in order of increasing scale

Experiment	Results
Attraction of balls to rings [Lon76].	On scale of 4–30 cm, $G(r)/G_0 = 1 + (2.0 \pm 0.4) \times 10^{-3} \ln (r/1\,\text{cm})$.
Mass, suspended from torsion balance, probing field inside a tube [Sper80].	For $\lambda = 1$ cm, 1 m one has $|\alpha| < 10^{-3}$, 10^{-1}, respectively.
Pumped hydroelectric reservoir at Splityard Creek [Moor88].	For effective range of 22 m, agreement with G_{lab} to 1% at one standard deviation.
Pumped hydroelectric reservoir, at the Hornberg Lake [Mül89].	For effective ranges of 40–70 m, agreement with G_{lab} to $(0.25 \pm 0.40)\%$.
300 m Erie Tower experiment [Spe90; Cru91].	Signal at top of tower was (21 ± 27) μGal. This yields approximate limits of $|\alpha| \leq 10^{-2}$, 10^{-3} for $\lambda = 10$ m, ≥ 100 m, respectively.
BREN Tower experiment [Thom89], 465 m.	Null result with systematic. Anomaly at top of tower was (-60 ± 95) μGal.
North Carolina tower experiment on 600 m scale [Eck88; Rom89; Jek89, 90].	Attractive force first reported with $\alpha \sim 0.0204$, $\lambda \sim 311$ m. Reanalysis, after corrections to field gravity survey, yielded an anomaly consistent with a null result.
Airy experiment in Mt. Isa and Hilton mines [Sta78, 81a,b, 83, 87a,b, 88, 89; Hol84, 86; Tuc89], on 1000 m scale.	Repulsive force reported with $\alpha \sim -0.01$, and λ about hundreds of meters. Results are being reevaluated because of necessary corrections to field gravity survey.
Airy experiment through Greenland ice cap [And89a,b; Zum90], on 1600 m scale.	Signal which could be interpreted as attractive force with $\alpha \sim 0.024$–0.035 for $\lambda \sim 5.4$ km–225 m. However, also consistent with large-scale intrusions of high-density material in bed rock.

Hills [Hills86] has proposed placing two self-gravitating objects in high earth orbit, at one of the Lagrange points so as to avoid tidal disruption. Two objects of a metric ton each at a separation of 100 m would orbit in 100 days. The relative change in period in an eccentric orbit would allow a clean search for a non-Newtonian force (see also [Avr86]).

Mufti et al. [Muf89] have proposed doing a small-scale Gauss' law experiment. They would precisely measure the gravity along the six faces of a cubic volume with linear dimension 5 m. They hope to detect a violation of Gauss's law down to a value of $|\alpha| \leq 2 \times 10^{-4}$ if $100\,\mathrm{m} \leq \lambda \leq 10^6\,\mathrm{m}$. This claim is probably too strong. In their calculations they used the earth's average density instead of the density near the surface. Also, they have very optimistic hopes for the precision of gravimeters and tilt meters.

However, note that no claim could be made by Mufti et al. regarding the value of λ, but only regarding the kind of bounds that could be obtained on α for a given λ. This demonstrates once again the usefulness of the theorem that, for a Yukawa force of range λ, it is necessary to have either very precise data or else measure over a distance scale given by λ to obtain any information on λ [GolA71a, b]. Here the scale size of the apparatus is 5 m. The Yukawa forces that might be found would have much longer ranges than that. Therefore, the experiment would only see a loss of flux, but not be able to give the fall-off scale.

Finally we mention the proposal to determine $G(r)$ by taking measurements at an open pit mine being excavated [Bru89]. This is delightfully similar in spirit to the oil [Yu79] and water [Moor88; Mül89] experiments mentioned above. Further discussions of tests of the inverse-square law can be found in [Pai87; Fis88b; Coo88; Fai88b; Cal89; Ade90a; Wil90a]. In table 2 we list some of the experimental results on tests of the inverse-square law which are important for the main topic under discussion.

4.3. *Tests of the principle of equivalence*

Starting in the late 1800's, Eötvös performed a series of principle of equivalence experiments, using a torsion balance he had developed for geophysical exploration [Eöt91]. (For a history of Eötvös' experiments with relevant references, see [Niet89a].) With his balance, Eötvös compared the relative acceleration of pairs of materials towards the earth. In a posthumous article, written twelve years after a forgotten first announcement [Eöt10; Niet89a], Eötvös et al. [Eöt22, 63] reported a null result at the 5×10^{-9} level, with individual comparisons being non-null at a few parts in 10^9.

In the following years, the principle of equivalence was verified to higher accuracy by the Dicke [Rol64] and Braginsky [Bra72] experiments. These experiments measured the relative acceleration of objects towards the sun to accuracies of 3×10^{-11} and 0.9×10^{-12}, respectively, at the 95% confidence level. Further, the positional data from the lunar laser-ranging experiments [All83] verified the principle of equivalence for the moon in comparison to the earth (the Nordtvedt effect) to an accuracy of 5×10^{-12} [Nor82]. Since the earth has a gravitational potential energy of 5×10^{-10} of its rest mass energy, this experiment verified the strong principle of equivalence to 1%. However, all these later experiments are long-ranged experiments, and would say nothing about the violation of the principle of equivalence by shorter-ranged gravitational forces.

Then, in 1986, Fischbach et al. [Fis86] created a sensation when they published their reanalysis of the Eötvös experiment. Fishbach et al. correlated the non-null results of Eötvös with baryon number per unit mass. (Different substances have different baryon numbers per unit atomic mass because of different nuclear binding energies.) Fischbach et al. concluded that this evidence was in agreement with the findings of Stacey's group on α, λ. From other motivations [Aro83a, b; Fis85] they further suggested this also was evidence for a vector force due to hypercharge [Fis86; Aro86], a "fifth force". (See [Niet89a; Ne'91] for discussions of Ne'eman's original [Ne'64] "fifth interaction" which was coupled to hypercharge.)

This announcement produced a great controversy. (For descriptions of the controversy see [DeR86; Bel87; Niet89a].) Firstly, the reanalysis was in error as to which sign [Tho86] for the proposed force was indicated by the raw data. Also, the magnitude obtained for the proposed new force was not that indicated by the mine data [Kim86]. In addition, it was realized that the interpretation of the values measured depends critically on the physical environment (topography and geology) within the range of the force (see [Mil86; Biz86; Neu86; Thi86] and chapter VII of [Sta87a]).

Finally, a hyperforce of this size can be ruled out [Lus86; Suz86; Bou86] by the lack of observed $K^+ \to \pi^+ +$ (unseen neutral) decays. (A calculation [Ali89] reporting that the unseen decays are not a problem for a hyperforce came to this conclusion by considering a separate contribution to the decay rate, which is small. It ignored the contributions from the diagrams of [Lus86; Suz86; Bou86], the interference between the small and large diagrams being negligible.)

Be this all as it may, the correlation found in the reanalysis was real. This finding stimulated numerous experiments, even though a non-gravitational origin to the correlation was suggested [ChuSY86].

The first experiments reported were by Thieberger [Thi87] and by Stubbs, Adelberger et al. [Stu87]. Thieberger looked for motion of a neutrally buoyant copper sphere in water, located at the edge of the New Jersey Palisades cliff. He reported a nonzero effect. It corresponded to an attractive force coupled to baryon number with $\alpha\lambda \sim 1.2 \pm 0.4$ m for $5\,\mathrm{m} \ll \lambda < 100\,\mathrm{m}$.

Adelberger's group looked for a differential rotation of two pairs of cylinders of beryllium and copper. The cylinders were hung as a torsion balance in a square pattern near the side of a small hill on the University of Washington campus. This group found no effect, with limits $|\alpha| \leq 2 \times 10^{-4}$ for $250\,\mathrm{m} \leq \lambda \leq 1.4\,\mathrm{km}$ and $|\alpha| \leq 1 \times 10^{-3}$ for $30\,\mathrm{m} \leq \lambda \leq 250\,\mathrm{m}$ (see also [Ade87]). The group's latest work claims a very stringent limit on a possible, single anomalous interaction for ranges $1\,\mathrm{m} < \lambda < 20\,\mathrm{km}$ [Hec89; Ade90b]. The authors report limits on $|\alpha|$ which range from about 10^{-3} for $\lambda = 1$ m to about 10^{-6} for λ from about 1 to 20 km. Their limits on $|\alpha|$ for the longer distances in this range depend on the accuracy of the topographic and underlying geologic data of their regional model out to 40 km in all directions for which no error budget has been given.

Now the Palisades is the edge of high-density diabase sill, which extends over 100 km to the west. The two experiments might be compatible if there are two longer-range vector and scalar forces which approximately cancel, thus explaining Thieberger's result [And88a]. This clearly implies that another experiment should be done at Thieberger's site [And88a,b].

Such an experiment is planned by Boynton [Boy90]. Boynton's group previously had performed a short-range experiment using a rotating-ring torsion pendulum at Index Mountain in Washington [Boy87], the ring being half beryllium and half aluminum. They found a signal corresponding to $\alpha\lambda = 2.3 \times 10^{-2}$ m for $\lambda = 100$ m. This was at the $3\frac{1}{2}$ standard deviation level, which could be taken as a very sensitive limit [Boy87].

At that point, the Boynton et al. result could have been taken as evidence for a force coupled to isospin [Boy87]. However, in a manner similar to the result ruling out hypercharge [Lus86; Suz86; Bou86], we showed that the absence of the same unseen decays $K^+ \to \pi^+ +$ (unseen neutral) ruled out an isospin force [Gold88b]. Further, it has now been reported [Boy90] that the original signal [Boy87] was not verified with an improved apparatus which, however, used different materials. (Boynton's Palisades experiment, with an improved version of his older apparatus, should begin shortly [Boy90].)

In any event, later experiments [Spe88; Cow88; Stu89; New89; Cow90; Nel90], culminating in that of Newman, Graham and Nelson [New89; Nel90], ruled out an isospin explanation. In [New89; Nel90] test masses were used composed mainly of lead and copper mounted on a torsion balance attracted to a lead ring in an aluminum shell. They found that for $\lambda \geq 1$ m, $\alpha_{\text{isospin}} = (-5.7 \pm 6.3) \times 10^{-5}$ and $\alpha_{\text{baryon}} = (1.2 \pm 1.3) \times 10^{-3}$. In fig. 4 we give a compilation of limits on possible isospin coupling strengths versus range that were obtained by various experiments.

Niebauer, McHugh and Faller [Nie88] used falling weights of uranium and copper in side-by-side absolute gravimeters to set a limit for a new force coupled to baryon number. They reported a limit given by $|\alpha\lambda| = 1.6 \pm 6.0$ m. This limit is valid for ranges from about 100 m to 1000 km, because [Nie88] it is sensitive to the mass directly below the apparatus and is not affected by horizontal mass anomalies. Even so, depending on whether or how any new forces are substance-dependent, one could still have an effect that would be seen in the Thieberger experiment but not in others [Hug88].

A number of other recent principle of equivalence experiments have found null results. A torsion balance experiment at Mt. Maurice in Montana by Fitch, Isaila and Palmer reported $\alpha\lambda = -0.05 \pm 0.09$ m [Fit88]. A torsion balance experiment was performed by Bennett near Little Goose Lock on the Snake River in Washington [Benn89a; Lon89; Benn89b]. For $\lambda \geq 200$ m, he reported $\alpha = (-0.5 \pm 1.0) \times 10^{-3}$. Kuroda and Mio [Kur89] used a free-fall interferometer to obtain the limit $|\alpha|\lambda < 9$ m, a value which gets smaller for $\lambda > 1$ km [Kur90]. Bizzeti et al. [Biz89] used a differential accelerometer composed of a solid sphere of plastic floating freely inside a saline solution. A representative limit is $|\alpha| < 0.3 \times 10^{-3}$ at $\lambda = 1$ km. (In [Riv89] hydrodynamic considerations are discussed.)

Principle of equivalence experiments have also been performed looking for effects on spin-polarized bodies (Dy_6Fe_{23}). Hsieh et al. [Hsi89] and Chou et al. [Cho90] looked for forces with a spin–gravity coupling. Relative to the gravitational forces of the earth and the sun, they found null results at the

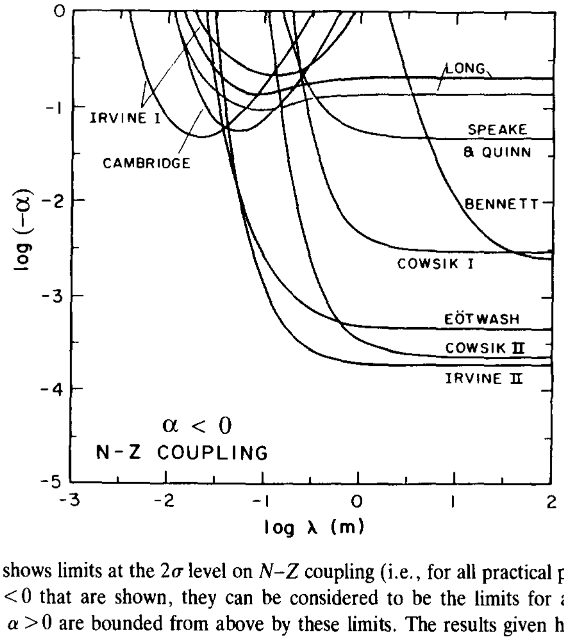

Fig. 4. This figure, taken from [Nel90], shows limits at the 2σ level on N–Z coupling (i.e., for all practical purposes, isospin) as a function of range, λ. Although it is only the limits for $\alpha < 0$ that are shown, they can be considered to be the limits for all $|\alpha|$ since (with the exception of the Cambridge data) the limits obtained on $\alpha > 0$ are bounded from above by these limits. The results given here were all obtained from experiments that used controlled local source masses. Irvine I is [Hos85], Cambridge is [CheY84], Speake and Quinn is [Spe88], Bennett is [Benn89a], Cowsik I is [Cow88], EötWash is [Stu89], Cowsik II is [Cow90], and Irvine II is [Nel90]. The area between the two curves labeled "Long" is the positive signal reported in [Lon76].

Table 3
Some principle of equivalence tests, listed in approximate order of first report of results

Experiment	Results
Motion of neutrally buoyant copper sphere in water, at edge of Palisades Cliff [Thi87].	Found effect corresponding to an attractive force coupled to baryon number with $\alpha\lambda \sim (1.2 \pm 0.4)$ m for $5\,\mathrm{m} \ll \lambda < 100$ m.
Search for differential rotation of two pairs of cylinders of differing materials hung on a torsion balance near a hill on the University of Washington campus [Stu87, 89; Hec89; Ade90b].	Original report found no effect with limits $\lvert\alpha\rvert \leq 2 \times 10^{-4}$ for $250\,\mathrm{m} \leq \lambda \leq 1.4$ km and $\lvert\alpha\rvert \leq 1 \times 10^{-3}$ for $30\,\mathrm{m} \leq \lambda \leq 250$ m. Recent work claims a stringent limit $\lvert\alpha\rvert < 10^{-3}$–$10^{-6}$ on a single anomalous interaction for ranges $1\,\mathrm{m} < \lambda < 20$ km [Hec89; Ade90b].
Search for frequency variation of half beryllium and half aluminum rotating ring on a torsion fiber at Index Mountain in Washington [Boy87, 90].	A $3\frac{1}{2}$ standard deviation signal, or corresponding limit, was found of $\alpha\lambda = 2.3 \times 10^{-2}$ m for $\lambda = 100$ m. (An isospin coupling was suggested.) It has now been reported that the original signal was not found with a different apparatus.
Falling weights of uranium and copper in side-by-side absolute gravimeters [Nie88].	Limit for a force coupled to baryon number of $\lvert\alpha\lambda\rvert = 1.6 \pm 6.0$ m, for $100\,\mathrm{m} \leq \lambda \leq 1000$ km.
A suspended ring torsion pendulum, made of semicircular sections of lead and copper, is attracted to lead columns [Cow88, 90].	A final result was obtained of $-2.3 \times 10^{-4} \leq \alpha_{\mathrm{isospin}} \leq 2.7 \times 10^{-5}$, for $\lambda \geq 3$ m.
Free-fall interferometer [Kur89, 90].	Limit, for baryon coupling, of $\lvert\alpha\rvert\lambda < 9$ m.
Motion of a solid sphere of plastic floating freely inside a saline solution, at Vallombrosa [Biz89].	A representative limit is $\lvert\alpha\rvert < 0.3 \times 10^{-3}$ at $\lambda = 1$ km.
Used lead and copper test masses on a torsion balance attracted to a lead ring in an aluminum shell [New89; Nel90].	For $\lambda \geq 1$ m, $\alpha_{\mathrm{isospin}} = (-5.7 \pm 6.3) \times 10^{-5}$ and $\alpha_{\mathrm{baryon}} = (1.2 \pm 1.3) \times 10^{-3}$.

levels of $(1.1 \pm 7.8) \times 10^{-9}$ and $(3.1 \pm 4.0) \times 10^{-8}$, respectively. Ritter et al. [Rit90] searched for an anomalous spin–spin dipole interaction. Compared to the standard magnetic dipole interaction, they obtained a null result of $(1.6 \pm 6.9) \times 10^{-12}$. See ref. [Hal91] for an advocacy of the existence of spin effects in nuclei. Other new effects also have been proposed [Fis88a; Wat88; Tal89].

For more details on these and other experiments we refer the reader to the original articles and to reviews on the subject [Pai87; Fis88b; Coo88; Fai88b; Cal89; Ade90a; Wil90a]. In table 3 we list some of the experimental results on tests of the principle of equivalence which are important for the main topic under discussion.

Before proceeding, however, we should comment on the report of Hayasaka and Takeuchi [Hay89], who reported an anomalous weight reduction (order of milligrams) of gyroscopes rotating right-handedly (not left) about the earth's vertical axis. The reduction was on the order of milligrams out of on the order of 175 g, for rotations of 3000–13 000 rpm. (This recalls the observations of Laithwaite, on the weight reduction of rapidly-rotating large gyroscopes [Walg74; HugH77].) However, a number of groups [Fal90; Qui90; Lut90] could not duplicate the result, with limits approximately 30 times smaller than the quoted effect.

4.4. Astrophysics experiments

Gibbons and Whiting [Gib81] noted that a combination of earth and earth satellite measurements could yield a limit on the product $\lvert\alpha\lambda\rvert$. Later, their results were improved upon by Stacey, Tuck and collaborators [Sta87a], who had available an improved geophysical value of local g. Stacey et al. used a preliminary analysis of Rapp, who had analyzed the mean free-air gravity anomalies over the 60% (38 152) of the earth's 1° × 1° areas which have reliable surface gravity observations. This yielded a value, for equatorial gravity of $g_e = 978.0326(5)\ \mathrm{cm/s^2}$. (The final analysis appeared in [Rap87].) From the value of GM_e obtained from laser ranging to the LAGEOS satellite [Smi85], one obtains $g_e = 978.0324(3)$. Ascribing this difference to a single, new gravitational force, [Sta87a] obtained what has come to be known as the "Rapp bound,"

$$|\alpha\lambda| < 14\ \mathrm{m}\,. \tag{4.10}$$

However, this length is probably too small for a conservative limit. A number of problems exist in extrapolating the surface measurements to sea level [Sta87a]. Further, the types of observational biases described by Bartlett and Tew [Bart89a,b,c, 90] must be considered. Since LAGEOS is at an altitude of ~6000 km, a lower-altitude satellite could provide useful information.

This leads to the observation that previous lunar orbiters have not had precise tracking information. Satellites in low and/or eccentric orbits about the moon which yielded such data would provide useful information on new gravitational forces in the critical range tens to hundreds of km. Such information is difficult to obtain locally because of the earth's atmosphere. This would be an example of the observation by Will that space experiments could provide useful tests in this regime [Wil89b].

Referring back to eq. (2.1), we can remind the reader that there is one other area (besides "static" antimatter experiments) where one can obtain useful information on a and b not in the combination of $a - b$, even if $a \cong b$ and $v \cong s$. This is in relativistic experiments. Indeed, that is why we were able to obtain the rough bounds for $a \cong b$ in eq. (2.10) from the rapidly rotating pulsar.

The first such limit was obtained in [Mac84]. The authors considered the shift of the perihelion of Mercury and the solar Eötvös results. They concluded that long-range new forces were possible if the coupling constants were properly matched. But further, they observed that a test might come with a study of the gravitational radiation from the binary pulsar PSR 1913 + 16. The usefulness of such a test would depend on the true departure from symmetry of the system, since vector and scalar radiation would be suppressed with symmetry.

Later, when more precise information on the binary pulsar PSR 1913 + 16 had been obtained [Weis84], Ford and Hegyi considered tensor–vector–scalar radiation in the large scale limit [For89]. (For our purposes this means $v, s \gg 1.4 \times 10^6$ km which is equal to the major axis of the system.) They found, from the agreement of the observed orbital decay with the tensor gravity predictions of gravitational radiation, that $|a - b| < 0.003$ and $0 \leq b \leq 0.12$. This means that for significant new forces to exist, say $a = b = 0.1$, they must be shorter-ranged than this particular astronomical scale. Otherwise, gravitational radiation due to them would have been inferred.

With the discovery of the 685 second binary 4U 1820 − 30 [Ste87], a new laboratory was opened. This is a more asymmetric system, but unfortunately not as well understood. It is thought to be a neutron star in orbit with a low-mass ($0.055 M_{\mathrm{sun}}$) helium white dwarf, with mass transfer occurring. Brans–Dicke radiation has also been studied using information from both this system and the binary pulsar [Wil89a].

By analyzing light and microwave deflection about the sun, limits on a single Yukawa force were obtained on the same scale. The limits given were approximately $|\alpha| < 0.02$ for $\lambda = 7 \times 10^7$ km and $|\alpha| < 0.3$ for $\lambda = 7 \times 10^5$ km [Riv86].

Redshift tests from space are also possible. The rocket experiment of Vessot and collaborators [Ves80], which took an atomic clock up to a final altitude of ~10 000 km above the earth, found an agreement of the frequency shift with general relativity to an accuracy of 70×10^{-6}. Although this experiment was not designed to provide bounds on possible new gravitational forces, in principle such an experiment could do so [Bel87; Hill88; Hug89a, 90a]. However, the bounds from this particular experiment are not as stringent as they could have been because data could only be used from between 10 250 km and 5560 km above the earth's surface. For ranges of new gravitational forces even of the order hundreds of km, the signal would be damped. Obviously, other redshift experiments in space are called for [Kri90b]. (We also refer the reader to the recent Saturn redshift [Kri90a] and Kennedy–Thorndike experiments [Hils90].)

A proposal to perform a combined redshift and ether-drift experiment has been made [And91]. It would be performed by placing synchronous atomic clocks in deep ocean sites, on high mountain tops, at sea level, and at the north pole.

Finally, the difference in the arrival times of the photons and neutrinos from supernova 1987a was less than three hours. Since, as we mentioned previously, the principle of equivalence predicts a time delay of one to six months from traversing our galactic gravitational field, this meant the time delays for photons and neutrinos were equal to a few tenths of a percent [LonM88; Krau88].

5. The Morrison argument

5.1. Invariance principles

The Morrison argument, given in section 1.2, may be summarized thus: if one had "antigravity", a matter–antimatter pair on the earth's surface could be raised adiabatically to height L with no loss of energy. Then the photonic energy obtained from the pair's annihilation would be blue-shifted in going back to the earth's surface. Thus, when the energy would be reconverted into the pair, the pair would have acquired kinetic energy; energy would not be conserved. We proceed with some points to keep in mind while traversing the argument.

If you have a Lorentz-invariant, quantum field theory, then energy *is* conserved. That is a matter of principle. No matter what kind of coupling the spin-one and spin-zero partners may or may not have, this must be correct. To avoid being confused, it is essential to remember that one has to be very careful how one assigns the energy of a system between the two particles involved and the field between them. This is especially true if one considers things in the external- (or central-) field approximation. It is only the total energy that is conserved, not the energy of the individual particles or even the energy of both particles. This is the same sort of care that must be taken with gauge invariance in electromagnetism. To clarify this point we now give four examples of how one can be led astray if one is not careful in treating these matters.

(i) *Galilean invariance from Lorentz invariance.* There used to be an apparent paradox [Barn69] called the "πN ambiguity." When starting with the pion–nucleon (πN) coupled field equations and taking the nonrelativistic limit, people did not obtain Galilean-invariant physics. The resolution boiled down to understanding how to go properly to the central-field approximation (static nucleon surrounded by a pion), in particular when using a time-dependent, unitary, Foldy–Wouthuysen transformation [Niet77].

(ii) *Gauge invariance in electrodynamics.* A few years ago it was proposed [Fis84] that the Washington g-2 experiment had reached its limit because quantum corrections to (what amounted to) the Casimir effect on the electrodes were as large as the accuracy of the experiment. However, Boulware, Brown and Lee [Boul85] pointed out that there was a violation of gauge invariance in the calculation of [Fis84]. When the calculation was corrected, using a gauge-invariant Foldy–Wouthuysen transformation, the new Casimir effect disappeared.

(iii) *Gauge invariance in electroweak physics.* There was a proposal [Eli74] that there be a Cabibbo mixing theory for leptons including massive ν_μ and ν_e neutrinos. Then, both neutrinos would couple to both muons and electrons. This led to relatively large predictions for the decay rates for $\mu \rightarrow e\gamma$ and $\nu_\mu \rightarrow \nu_e\gamma$. However, the critical matrix element in eq. (2.7) of [Eli74] involves $\varepsilon_\mu \langle \bar{e}|\gamma^\mu(1-\gamma^5)/2|\mu\rangle$. This is not gauge invariant since it couples the photon to a nonconserved (electromagnetic) current. Gauge-invariant calculations followed [Chen77; Gold77], involving a magnetic transition with $\sigma^{\mu\nu}q_\nu$ replacing γ^μ in the above. The predicted maximal decay rates are dramatically smaller for the gauge-invariant results.

(iv) *The slingshot effect.* Perhaps the most amusing analogy comes from space physics, the "slingshot effect" used in the classic "tour of the planets" [Barg73]. When a spacecraft is sent to Uranus, it can obtain kinetic energy by going around Jupiter. (In the standard discussion [Barg73], the spacecraft's initial velocity in the heliocentric frame is chosen to be on the order of Jupiter's orbital velocity and when it reaches Jupiter it will have a conservative hyperbolic orbit in the Jupiter-centered frame.) In the heliocentric system, the energy obtained from the Jupiter encounter is maximum if the spacecraft leaves in the direction of the planet's motion around the sun. Then the magnitude of the spacecraft's final velocity (in the heliocentric system) will be the sum of the magnitude of its initial velocity (in the Jovian system) and the magnitude of Jupiter's orbital velocity (in the heliocentric system). But if one considers things in a heliocentric, central-field approximation, and ignores the loss of energy of Jupiter in the flyby, one would think that energy is not conserved in Newtonian, nonrelativistic celestial mechanics.

With the above problems in the back of our minds, below we will go through matter–antimatter interaction loops with redshift arguments as Morrison [Mor58b] did. Remember that the calculations are done in the external-field approximation. Also, for simplicity we are considering the case where all the forces are infinite-ranged. For finite-range forces the arguments are slightly more complicated, but still follow.

5.2. Tensor gravity

We begin with a discussion of normal tensor gravity. In fig. 5, consider a matter–antimatter pair of particles at point A, on the surface of the earth. (We approximate the local potential by gz.) For the pair to go from point A to point B it needs to have kinetic energy at point A, because the gravitational force of the earth on both the particle and the antiparticle is attractive. So, the pair has to start out from point A with total energy

$$E_A = 2mc^2 + \text{kinetic energy}\,. \tag{5.1}$$

The pair reaches point B with all the kinetic energy having been exchanged for potential energy $(2mgL)$,

$$E_B = 2mc^2 + 2mgL\,. \tag{5.2}$$

The pair is converted to a "photon" at point C.

Of course, in actuality there would be a photon pair. One can go through the gedanken exercise of placing a coupled pair of mirrors above C and below D (see fig. 5 and the discussion below) so that the two photons arrive at D at the same instant without a net change in their total energy or momentum. Alternatively, one may just think of a single off-shell photon, but this requires some care to maintain gauge invariance.

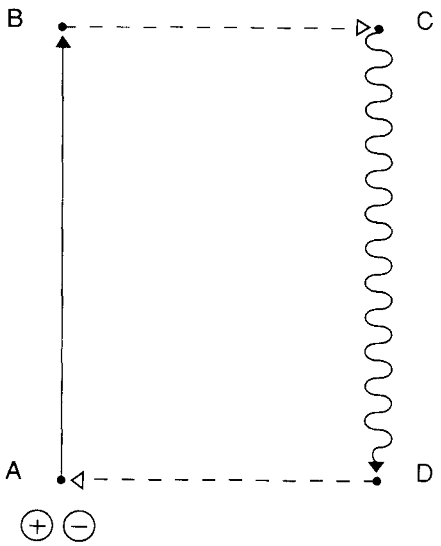

Fig. 5. The particle–antiparticle loop of the Morrison argument. The pair starts at point A and then rises vertically through the gravitational field under discussion to point B. There the pair annihilates into (in this approximation) a single photon. The photon starts from point C down through the gravitational field under consideration to point D. There it reconverts into the pair, which can again restart from point A.

Now we have reached the critical question. At point C, what is the photon's "energy", i.e., the zeroth component of its four-momentum? It must be

$$h\nu_c = 2mc^2 \,. \tag{5.3}$$

This is because locally the photon does not measure what "absolute potential" it is in. The annihilation process is only sensitive to the rest energy and kinetic energy of the pair in their center of momentum frame.

We must think of the coupled field equations, including the Einsteinian field, to make sense of this. Remember, the "single photon" is also in the gravitational field of the earth and we must account for its being in that field. Whatever distortion of the gravitational field was caused by the pair, was also caused by the "photon" of the same energy. (Here we see explicitly that in reality two photons are needed. The stress-energy tensor of the particle pair is not traceless, whereas that of a single on-shell photon should be.)

So, whatever absolute gravitational potential we may want to think the pair is in, the "photon" is in the same potential. It is only in traversing the gradient of the gravitational potential (irrespective of the magnitude of the potential itself) that the photon is affected. Therefore, the $2mgL$ in eq. (5.2) does not belong in eq. (5.3).

The "photon" will blue-shift in going between points C and D. It ends up at point D with energy

$$h\nu_D = h\nu_C + h\,\Delta\nu_{CD} = (2mc^2)(1 + gL/c^2) \tag{5.4}$$

$$\approx 2mc^2 + 2mgL \,. \tag{5.5}$$

This is the energy necessary to create a new pair at point A which will have enough kinetic energy to travel up to point B again.

Of course, the total energy of the "photon" has not changed (in the conservative system) just as that of the pair has not changed. The gravitational potential energy of the photon at C (relative to D) has been hidden in the general relativistic renormalization at C of the clock rates used to measure the photon frequency implicit in eq. (5.3) [Schi60; Dic60; Thir61; Nor75; Unr79]. What is expressed in eq. (5.5) is that the photon at D has sufficient energy to produce a pair, at rest, at point B. In the following we will continue to use this straightforward description, essentially in terms of a flat, reference space–time rather than a clock-based description. This is because we wish to consider other, non-Einsteinian, interactions as well.

5.3. *Morrison's "antigravity" analysis*

Morrison started with "antigravity", regular tensor gravity on matter but opposite sign gravity (repulsion) on antimatter. Therefore, there is no force on the pair. Thus, the pair can start at point A with zero kinetic energy and can be raised adiabatically to point B. It then converts to a "photon".

The photon, starting down from point C, has the energy that the original pair had at point A,

$$E_{\mathrm{A}} = 2mc^2 = h\nu_{\mathrm{C}} . \tag{5.6}$$

The photon now falls in the gravitational field and thereby gains the additional energy

$$h\,\Delta\nu_{\mathrm{CD}} = h\nu_{\mathrm{C}}(gL/c^2) = 2mgL . \tag{5.7}$$

The pair recreated at point A now has energy given by the sum of eqs. (5.6) and (5.7), and so energy conservation is violated with (tensor) "antigravity". Morrison was correct. Note that Morrison made no negative statements about (what we now know to be) consistent field theories. Such statements have been made by others.

5.4. *Gravivector field*

We can now go through the same loop with gravivector coupling by itself, ignoring tensor-gravity contributions. Because the sign of the coupling to the gravivector field is opposite for matter and antimatter, the discussion is the same as in section 5.3 for "antigravity" up to point C. The pair adiabatically rises from point A to point B (without any net effect from the gravivector field) and then converts to a photon with energy $2mc^2$ at point C. But here, since the photon does *not* couple directly to the gravivector, it does *not* experience a blueshift from the gravivector field in falling back to the earth at point D. So, energy *is* conserved. (See section 8.1 for a discussion of the existence of more general vector couplings.)

5.5. *Graviscalar field*

In considering the graviscalar field (and again ignoring tensor-gravity contributions), one is tempted to start out the same way as for "antigravity" and gravivector coupling, except one cannot start out the same way. One cannot adiabatically raise the pair from point A to point B without changing their total energy because the force on both the particle and the antiparticle is attractive, as with tensor gravity. So, again as for tensor gravity, energy is needed to go between point A and point B.

The pair has to start out from point A with total energy

$$E_{\mathrm{A}} = 2mc^2 + \text{kinetic energy}\,. \tag{5.8}$$

The pair reaches point B with the kinetic energy having been exchanged for potential energy ($2mg_{\mathrm{S}}L$),

$$E_{\mathrm{B}} = 2mc^2 + 2mg_{\mathrm{S}}L\,. \tag{5.9}$$

We will assume here that the scalar is coupled only to the trace of the stress-energy tensor. The value of this trace is unchanged for the "photon" from the value for the particle pair. Therefore, if there is no physical meaning to the absolute potential, the "photon" at point C will again have energy

$$h\nu_{\mathrm{C}} = 2mc^2\,. \tag{5.10}$$

Again the "photon" is blue-shifted by $2mg_{\mathrm{S}}L$ in traveling through the graviscalar field between point C and point D. (Since the "photon" is actually two or more on-shell photons, consistency then demands that there be a particular graviscalar coupling to on-shell photons.) Therefore, the new pair at point A has sufficient kinetic energy to undertake the next cycle. (See [Bel87; Hug89a, 90a] for the basis of an equivalent description in terms of clock rates at two levels. Then there is not an overt blueshift from coupling to the photons.)

Alternatively, if there is a physical meaning to the absolute scalar potential, we would need to know its value. Assume, for the moment, it is indeed $2mg_{\mathrm{S}}L$. Then the "photon's" total energy would be

$$E(\nu_{\mathrm{C}}) = 2mc^2 + 2mg_{\mathrm{S}}L\,, \tag{5.11}$$

but the last term would be only *potential* energy. That is, the scalar background field acts as a medium, so the index of refraction for the "photon" is not that of a *free*, *noninteracting* one.

However, now as the "photon" descends from C to D, it converts the last term in (5.11) from potential to kinetic energy. Therefore, $h\nu_{\mathrm{D}}$ has just the correct value to produce the particle–antiparticle pair with enough kinetic energy to once again rise to the height L.

5.6. *Graviscalar field coupled to electromagnetism*

As mentioned in chapter 2, one can also have graviscalar fields that are coupled directly to electromagnetism via the square of the field-strength tensor [Hill88; Hug89a, 90a]. Once again, these are consistent field theories and so will conserve energy. The way to understand things in this context is, not surprisingly, with a combination of the arguments of sections 5.4 and 5.5 above. The produced "photon's" total energy is affected by the additional coupling. Further, there is an additional blueshift due to the graviscalar field, but this is just compensated for by a difference in clock rates as measured by photons versus other clocks (see [Bel87; Hug89a, 90a]).

5.7. *Newtonian gravity using an apparent paradox*

Now let us return to Newtonian gravity, in particular to eq. (5.2). If we had made the choice of saying that eq. (5.3) for the photon energy should be the same as (5.2), then we would have ended up at eq. (5.5) with

$$h\nu_{\mathrm{D}} = h\nu_{\mathrm{C}} + h\,\Delta\nu_{\mathrm{CD}} = (2mc^2 + 2mgL)(1 + gL/c^2) \tag{5.12}$$

$$\approx 2mc^2 + 4mgL\,. \tag{5.13}$$

Then Newtonian gravity would have ended up as a perpetual motion machine. That is, if one insisted on doing things this way, with a physical meaning to the absolute potential, gravity would violate energy conservation! Potential energy is not a relativistically invariant quantity.

We point out in chapter 7 that Good recognized this problem when he formulated his argument. Good asked [Goo61] if we are in the gravitational potential of the earth, the sun, the galaxy or the universe. Depending on the answer one could make Newtonian tensor antigravity appear to be a bigger and bigger energy violator at will.

From this point of view, where antigravity fails is in not having needed the kinetic energy ($=2mgL$) to get from point A to point B. The antimatter pair gets to point B still having zero potential energy. Therefore, in contradiction, the photon has to have both (i) $h\nu_{\mathrm{C}} = 2mc^2$ (think of points B and C as being at infinity if you want); and also (ii) $h\nu_{\mathrm{C}} = 2mc^2 - 2mgL$, because the photon has obtained energy from matter in an "Einstein field."

To summarize the above, in Lorentz-invariant field theories of gravity involving matter–antimatter pairs, there is no problem with energy conservation. However, the general question of the relation of the redshift of photons (or clock rates at differing potentials) to gravity as measured on matter also needs to be addressed. We will do so in section 8.1.

6. The Schiff argument

6.1. *QED vacuum polarization and the principle of equivalence*

The argument of Schiff [Schi58, 59] has been described [Scu89; Eri90] as ruling out any anomalous gravitational behaviour of antimatter. However, Schiff's argument only dealt with "antigravity" theory [Seg58]. As we have pointed out, "antigravity" theory does not conserve energy. Therefore, it is necessary to reexamine what Schiff actually did before generalizing its applicability to modern theories of gravity.

Schiff had a very difficult task. He wanted to consider quantum field-theoretic corrections to a quantum field theory of gravity coupled to matter, when quantum general relativity coupled to matter is not renormalizable at even the one-loop level. Instead of addressing the stress-energy tensor directly, he chose to focus on the probability of finding an antiparticle in a nominally particle state, arising from one-loop fluctuations due to electrodynamics. He then multiplied this probability by the mass of the positron to obtain a scale of the "antigravity" interaction energy with the earth's potential. The differences of this (net) quantity for atoms of differing atomic number, Z, was then compared with the constraints of the Eötvös experiment.

There are three problems with this approach.

(1) The probability of finding an almost on-shell antiparticle in a particle state is a divergent quantity in QED (or any other gauge theory for that matter). In modern terms, this is the probability distribution of virtual partons as a function of the momentum fraction (of the original state) that they

carry [Fey72]. This distribution diverges for low momentum fraction rapidly enough so that the integrated total probability also diverges, although the momentum fraction carried does not diverge.

Schiff observed the divergence, but argued that he could obtain a lower bound on the probability by doing a perturbation calculation, dropping the explicitly infinite piece of the expansion, and retaining only the calculated finite part. Explicitly, in his eq.(16) Schiff calculated [Schi59]

$$E_{\mathrm{C}} \cong E_0(1+\phi) - (1+\phi)\sum E_{\mathrm{P}}^{-1}|\langle \mathrm{P}|H_{\mathrm{C}}|0\rangle|^2 - 2mc^2\phi \sum E_{\mathrm{P}}^{-2}|\langle \mathrm{P}|H_{\mathrm{C}}|0\rangle|^2 , \tag{6.1}$$

where P denotes the pair states and E the energy. The second term, which he dropped, is divergent. He kept the finite third term. This is clearly inconsistent with a modern, proper renormalization approach. The implications of the above procedure for every other renormalized constant in the theory are uncontrolled – we do not even know the implications for the experimental determination of α_{em} due to this procedure. Its renormalized value may now be quite different from the standard value. Another way to express this point is that we have no way of knowing what finite parts should be included in the infinity discarded by Schiff. The correct answer could include all of the remainder he used to derive conclusions regarding the gravitational properties of antiparticles.

(2) Schiff probably chose this course because he focused on the particle mass as defining the coupling strength to gravity, rather than on the contribution to the stress-energy tensor. If one considers anomalous couplings of antiparticles to gravity a little more generally, then even for an "antigravity" scenario of the type one is addressing, it is more reasonable to put an anomalous sign in front of the antiparticle contribution to the stress-energy tensor as it couples to tensor gravity. Then, instead of the (anti)particle mass times an ill-defined probability, one finds the expectation value of the antiparticle contribution to the stress-energy tensor as the quantity which determines the possibly anomalous antiparticle contribution. This is not divergent, and so can be bounded by the sum of the loop contributions involved.

For the vacuum polarization contribution to the QED Lamb shift considered by Schiff (the Uehling potential energy [Ueh35]), one can calculate that ($\hbar = c = 1$)

$$\Delta E_{nl} = (4\alpha_{\mathrm{em}} e^2/15 m_{\mathrm{e}}^2)|\Psi_{nl}(r=0)|^2 \tag{6.2}$$

$$= -(8\alpha_{\mathrm{em}}^3/15\pi n^3) Ry\,\delta_{0l} , \tag{6.3}$$

in a physical gauge (see fig. 6). For the $2\mathrm{s}_{1/2}$–$2\mathrm{p}_{1/2}$ states, this total energy shift of $\Delta E = -27\,\mathrm{MHz} = -1.1 \times 10^{-16}\,\mathrm{GeV}$ is to be compared to the total energy of the hydrogen atom, 0.94 GeV. Even if all this energy were to be associated with violation of the principle of equivalence due to the positron, this is only a part in 10^{16} of the entire energy content. Even today, experiments are not accurate enough to discern deviations from normal gravity for such small contributions.

(3) Further, the Schiff calculation is entirely moot in modern theories of quantum gravity. The anomalous behaviour of antimatter, which can arise in such theories, is due to a combination of vector and scalar interactions of gravitational strength, beyond the usual tensor interaction. The vector contribution from fermion loops, such as those that exercised Schiff, simply cancel to zero in leading order in the gravitational coupling.

To find a bound on the anomalous effects, one must now calculate the effect of the absence of this contribution, while those from the vector coupling to the fermion line in the other vertex correction graphs remain. However, as before if the vector coupling has gravitational strength, the fractional effect

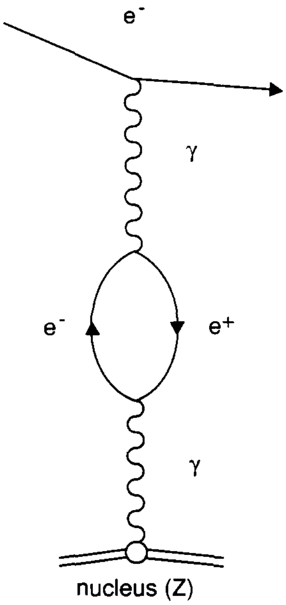

Fig. 6. The vacuum polarization Feynman diagram in QED.

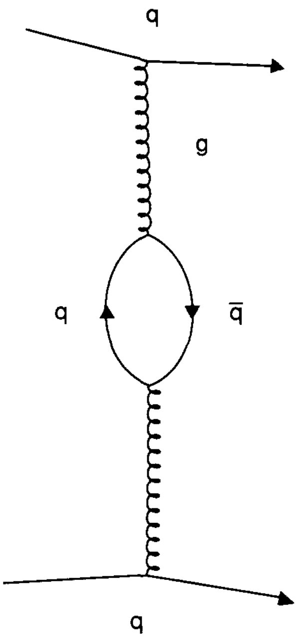

Fig. 7. The vacuum polarization Feynman diagram in QCD.

is of order 1 part in 10^{16}, or more than seven orders of magnitude too small to have been seen in Eötvös experiments, or more than three orders of magnitude if gluonic terms are considered (see the following section).

The Schiff argument depends upon identifying antifermion (positron) components in an atom via vacuum polarization effects, and does not examine any other sources of antimatter. Recently, Hoyer has described a method to obtain a Fock-space expansion of QED bound states which would allow all sources to be examined [Hoy89]. To our knowledge, this type of approach has not yet been pursued vis a vis the present question.

6.2. QCD vacuum polarization

Finally, we recall [Gold85] that there is a potentially more serious loop correction than the electrodynamic one, but it is still not feasible to evaluate it either theoretically or experimentally. This occurs for the analog of the Lamb shift correction to the QCD strong interaction. Schiff did refer to this in terms of pions [Schi59]. However, he did not attempt a calculation because of an uncertain field theory of the strong interactions with its large coupling constants, these constants obviating the use of perturbation theory.

Today, we need to consider virtual quarks in QCD loops (see fig. 7). Unfortunately, the organization of nuclear structure is quite different from atomic structure. For QED, in principle we know of the Z dependence of the Uehling potential. Further, since $A \neq 2Z$, the effect per unit mass definitely varies with atomic species in a comparable way. However, the saturation property of the strong interactions in the nuclear medium makes it much more difficult to determine the component of the QCD – "Uehling" – potential that does not vary linearly with the number of nucleons in the nucleus. It is only to this deviation from linearity that weak equivalence violation experiments are sensitive.

Without a detailed quark picture of nuclear structure [Gold88c] we simply cannot evaluate how much of the four orders of magnitude available from the ratio of the squared coupling constants, $(\alpha_S/\alpha_{em})^2$, actually enhances the anomalous effects. Further, just as there are explicit ambiguities in the coupling of the graviscalar to the photon [Hill88; Hug89a, 90a], so too there can be these same ambiguities in the coupling of the graviscalar to the gluon. Nonetheless, it is clear that even Eötvös-type experiments with accuracies at the one part in 10^{12} level can only barely begin to address these questions.

7. The Good argument

7.1. The argument using absolute potentials

Myron Good came up with an ingenious argument against "antigravity" [Goo61]. Much to his credit, he thought of it even before *CP* violation was discovered.

Good observed that if the gravitational potential is explicitly assumed to have absolute meaning, then the energy difference between the K^0 and $\bar{K}^0$ due to "antigravity" should be $2M_K\phi_G$, where ϕ_G is the gravitational potential. Therefore, since the K_L is a linear superposition of the K^0 and $\bar{K}^0$, the K_Ls in a beam should instantaneously start regenerating some K_S because the relative time variation of the K^0 and $\bar{K}^0$ components is $\exp(i2M_K\phi_G t/\hbar)$. Since K_Ls did not regenerate K_Ss (as stated, this was *before* the discovery of *CP* violation), Good reasoned that this excluded the "antigravity" statement $\bar{g} = -g$.

However, in modern (as well as classical) gauge theories there is no meaning to an absolute potential for an infinite-range force. It is the potential *differences* that are important. For instance, consider a photon creating an e^+e^- pair in the middle of a condenser and assume the particles initially have identical kinetic energies, T_K. Although the electron and positron respond with opposite sign to the electromagnetic potential between the plates, their kinetic energies, and so therefore, their momenta do not begin to differ until they are separated by the electromagnetic force. This does not occur instantaneously. While it is true that their total energies are different $T_K \pm eV$, this does not produce an instantaneous difference in their phases, either. Their wavepackets must evolve in space and time, first.

Indeed, as Good himself discussed [Goo61; Goe 86], if one accepts an absolute potential for an infinite-range force, one immediately has a quandry. Is the gravitational potential of the earth, the sun, the galaxy, the local group, or the universe the correct one to use? The last possibility naively would give a potential energy on the order of the rest mass energy for any particle. (This fact was one of the intuitive bases of the steady-state theory of the universe. The positive energy needed to create a particle would be compensated for by being in the potential well of a local region the size of the Hubble radius.) Alternatively, if one takes ϕ_G to be zero locally, the proposed effect vanishes entirely.

On this point, we note that Kenyon recently took another look at the Good argument and claimed to obtain a bound on a violation of the weak principle of equivalence from new neutral kaon data [Ken90]. However, [Ken90] misinterprets [Mac84] and also fails to realize both the theoretical and experimental limits that can be placed on the use of absolute potentials (see chapter 5 and section 4.4). Once again, one can simply take ϕ_G to be zero locally, not at a point infinitely far from the "great attractor" referred to by Kenyon. We know of no independent experimental method to show that ϕ_G has any other local value, and insist this would have to be achieved for Kenyon's results to be accepted (see also [Cli90]).

Be this all as it may, Good's argument is still a useful tool with which to test the ideas of quantum gravity. If there is a new vector interaction, one has to ask what its coupling to antimatter is. One could take the K_L–K_S mass difference (3.5×10^{-6} eV/c^2) [PDG90] as providing a bound on regeneration from a new vector gravitational force. (Note that the K_L–K_S mass difference provides a *CPT* bound on the inequality of the K_0 and $\bar{K}_0$ masses.) The coupling is to the quark and antiquark in the $K^0(d\bar{s})$ and $\bar{K}^0(s\bar{d})$. Then it is a matter of calculation what a particular model yields. Some models will be excluded by this variant of the Good argument. However, others will not.

For example, if one takes the generation-independent coupling model of Macrae and Riegert [Mac84], there is no gravitational K_S regeneration and the K-mesons would propagate as in normal gravity [Gri88]. However, there still would be larger gravitational acceleration towards the earth of antiprotons relative to protons by up to a factor of three (assuming a, b are bounded by unity). When the vector and scalar partners obtain masses, the above statements are still true, except that the factor becomes smaller than three.

Finally, we mention a point that was recently reemphasized by Bell [Bel87]. When *CP* violation was discovered, it was asked if there might be a new vector force which was in fact the origin of what was only an "apparent" *CP* violation [Bel64; Ber64]. It was suggested that this weak force might be coupled to hypercharge. Weinberg looked at this suggestion and gave a lucid discussion on tests for "hyperphotons" [Wei64]. Many aspects of his arguments resemble the recent observations concerning non-Newtonian gravity reviewed here. Weinberg also discussed Ne'eman's hypercharge force [Ne'64].

This is relevant since Chardin has reopened this question in the context of "antigravity" [Char90]. An explanation of *CP* violation as really being an effect of "antigravity" would also strongly affect our current picture of the universe. Once again there would be no reason for the observed dominance of matter in the universe [Dol81] (see chapter 1). Further, one would have to worry about the lack of $K^+ \rightarrow \pi^+ +$ (unseen neutral) decays, as discussed in section 4.3, and rethink the possible energy dependence of *CP*-violation parameters. The data has tightened [PDG90] since the original proposal of a possible energy dependence in these parameters [Aro83a, b].

7.2. The argument independent of absolute potentials

In principle, a variant of the Good argument can be applied without making any presumptions about absolute potentials. To see this, first note that kaon beam-line lengths, l, range from a minimum of tens of meters up to a maximum of a few hundred meters (at FermiLab, for example), and are essentially parallel to the earth's surface. The more extreme lengths are possible because the product of the lifetime times the velocity of light, $c\tau$, is 15.5 m for the longer-lived, neutral-kaon (approximate) *CP* eigenstate. Further, the relativistic time dilatation factor, γ, ranges from a few to a few hundred. Therefore, not much more than an order-of-magnitude loss in kaon flux occurs during the transit.

One can therefore ask how far the centroid of the kaon beam will fall under normal gravity. To answer this, consider a particle in a spherically symmetric gravitational field. Then the general relativistic geodesic equations describing the situation are (see chapters 11 and 12 of [Lan75])

$$\frac{\mathrm{d}u^\alpha}{\mathrm{d}s} = \gamma\,\frac{\mathrm{d}u^\alpha}{\mathrm{d}\tau} = -\Gamma^\alpha{}_{\beta\gamma}u^\beta u^\gamma \equiv \gamma A^\alpha\,, \tag{7.1}$$

where the Γ are the Christoffel symbols, $u^\alpha = \mathrm{d}x^\alpha/\mathrm{d}t$ is the four-velocity defined in eq. (2.2) (meaning $\gamma\boldsymbol{\beta} = \boldsymbol{u}$ where γ is the standard relativistic factor), s is the proper distance, τ is the proper time, and A^α is, as of now, a definition. Here the nonzero components of the metric are given to first order by

$$g_{00} = (1 - 2GM/rc^2)\,, \qquad g_{ij} = -(1 + 2MG/rc^2)\delta_{ij}\,. \tag{7.2}$$

Straightforward calculation shows that

$$A = -(GM/r^3)[(1+\beta^2)\boldsymbol{r} - 2(\boldsymbol{r}\cdot\boldsymbol{\beta})\boldsymbol{\beta}]\,. \tag{7.3}$$

The relativistic four-force is

$$f^\alpha = \mathrm{d}p^\alpha/\mathrm{d}\tau = m\,\mathrm{d}u^\alpha/\mathrm{d}\tau\,. \tag{7.4}$$

However, the result (7.3) is obtained in a coordinate frame. The force f^α should be given in a local orthonormal frame. Upon transforming to such a frame, one obtains [Oku89a, b, 90]

$$\boldsymbol{F} = \boldsymbol{f}\sqrt{-g_{ii}} + m\,\frac{\mathrm{d}}{\mathrm{d}t}\,(\sqrt{-g_{ii}}\,\boldsymbol{u}) = -\frac{GMm\gamma}{r^3}\,[(1+\beta^2)\boldsymbol{r} - (\boldsymbol{r}\cdot\boldsymbol{\beta})\boldsymbol{\beta}]\,. \tag{7.5}$$

Now recall the relationship between force $\boldsymbol{F}$ and acceleration $\boldsymbol{a}$ in a local orthonormal frame [Oku89a],

$$m\gamma\boldsymbol{a} = \boldsymbol{F} - (\boldsymbol{F}\cdot\boldsymbol{\beta})\boldsymbol{\beta}\,. \tag{7.6}$$

Equations (7.3), (7.5) and (7.6) show that $\boldsymbol{a} = A$ is the acceleration in the local orthonormal system [Gold91a].

If $\boldsymbol{\beta}$ is parallel to $\boldsymbol{r}$ there is no acceleration in the extreme relativistic case. (Light does not accelerate falling down, it is only blue-shifted.) On the other hand, if $\boldsymbol{\beta}$ is perpendicular to $\boldsymbol{r}$, the acceleration is $-g(1+\beta^2)$. This agrees (in the limit $\beta \to 1$) with the factor of two in the bending of light going past the sun and also agrees with the different approximation that yielded the tensor term of eq. (2.1).

Returning to the issue at hand, the available transit times of kaon beams, t, range from 10^{-7} to 10^{-6} s in the lab frame. If both components of the kaon respond normally to gravity, the centroid of the kaon beam falls according to

$$d \cong \tfrac{1}{2}gt^2(1+\beta^2)\,. \tag{7.7}$$

After the transit, this distance is about 10^{-11} to 10^{-9} cm (or 100 fm to 0.1 Å) over the range of beam line lengths available. Now, what happens if the particle and antiparticle components (quarks or kaons) respond differently to gravity? The answer depends on the range of the quantum-mechanical coherence of the produced kaon wavepacket. If the coherence size were of the order of a kaon size (~1 fm), there would be no question that the components would separate sufficiently so that interference would have become impossible. An anomalous regeneration of short-lived neutral kaons in the beam would then be apparent.

Since the kaons are produced in individual beam hadron–target-nucleon collisions, it is difficult to imagine that the transverse coherence size at the production point, Δq_0, is much more than the order of a fermi. Unfortunately, the quantum-mechanical wave spreads out significantly from that point, in a well known fashion [Schi55; Kai83; Kle83], namely,

$$\Delta q = [(\Delta q_0)^2 + (t\,\Delta p/M_\mathrm{K})^2]^{1/2}\,, \tag{7.8}$$

where Δp is the (transverse) momentum uncertainty and the kaon mass is M_K. Because Δq_0 is so small, after very short times eq. (7.8) can be approximated as

$$\Delta q \cong t\,\Delta p/M_{\mathrm{K}} = t(\Delta p/p)(p/M_{\mathrm{K}})\,. \tag{7.9}$$

Equation (7.8) represents a minimum-uncertainty state at $t=0$. This would be a harmonic oscillator coherent state if $(\Delta q_0)^2 = \hbar/2m\omega$. However, contrary to a coherent state, this state is free, i.e. $\omega \to 0$, and it spreads with time. One can show that this spreading and limit on ω correspond to the free-particle limit of a squeezed state [Niet86].

The *fractional* momentum uncertainty $\Delta p/p$ at the production vertex is determined by the typical transverse momentum spread in soft hadronic processes, it being of order 300 MeV/c. This would give $\Delta p/p = 0.001$–0.1. Aperture-defining slits for the neutral kaon beam generally restrict this further. However, the best that it is possible to imagine that the kaon beam has been defined is to assume that $\Delta p/p$ is actually experimentally determined by the vertex resolution in the detector, r, divided by the distance from the production target. This means that we are using the location of the decay vertex as part of the state preparation for the kaon beam. Since the decay region is in vacuum, there is no other information available to constrain the kaon momentum state. Therefore, because r is typically of order 1 mm in meter-sized apparatus,

$$\Delta p/p \sim r/l \sim (10^{-4}\text{–}10^{-6})/3\,. \tag{7.10}$$

Finally, since $(p/M_{\mathrm{K}}) = \gamma v$ and $v \cong c$, one obtains

$$\Delta q \sim 0.3\text{–}30\ \mathrm{cm}\,. \tag{7.11}$$

Thus, even within these rough and generous order-of-magnitude estimates, it is very difficult to imagine that anomalous regeneration effects might become visible at the end of *any* beam line [Gold91a]. This would be true even for deviations much larger than those of order one between the gravitational responses of particles and of antiparticles. To achieve the order 1% accuracy goal of the antiproton gravity experiment would be even much more difficult. (In addition, there would be the requirement that a measurement of, or a bound on, the transverse coherenence size must also be made within any such experiment).

It is amusing to note, however, that in principle the effect *is* measureable. This is because the vertical separation of the packets grows quadratically with t while asymptotically the wave packet spread grows only linearly in t. Nonetheless, such a measurement would be a considerable technical achievement; at the far end of the beam line, the transverse scale we are considering subtends only on the order of 10^{-12} rad! At present, one must look for a roughly 1 Å shift in the centroid of a 1 cm wide wavepacket!

The above discussion describes the situation for a separation of particle and antiparticle components in a wavepacket by normal and "anomalous" tensor gravity. However, vertical changes in height may also be due to a transverse momentum of the beam. Thus, one must also consider the change in phase along the almost common paths of the particle and antiparticle components within the packet. This phase change is due to the possibly differing gravitationally induced change in momentum as a function of vertical location. Then it is straightforward to show that path-difference effects are negligible [Gold91a] and that

$$\hbar\,\Delta\theta = 2m\gamma(g-\bar{g})Lz/c\,, \tag{7.12}$$

where $m\gamma c^2$ is the beam energy, g and $\bar{g}$ are the gravitational accelerations on the two different components, L is the horizontal distance traversed by the beam, and z is the change in vertical height due to the small vertical momentum component.

Since the γ factor general-relativistically amplifies the phase-difference development, in this case the phase may change *too* rapidly across the vertical face of a detector for oscillations to be discerned. Thus, for a given vertical spatial resolution in a detector, higher-energy beams are more suited to searching for very small differences between g and $\bar{g}$ while low-energy beams are more sensitive to large differences. To achieve the latter may require the use of vertical kaon "beams". We are not aware of any experimental studies of neutral-kaon oscillations as a function of vertical location in detectors.

8. Conclusions

8.1. Experimental restrictions on anomalous antimatter gravity

A general consensus now exists [Pre90] that the antiproton gravity experiment is an important test of gravity and particle physics, independent of any particular theoretical motivation. Be this as it may, and even granting that the focus of this review is the set of classical arguments against "antigravity", in this article we have described, in some detail, experimental tests of the principle of equivalence and of the inverse-square law and their relevance to theories of quantum gravity.

Thus, at this point it behooves us to comment on what restrictions exist, coming from the experimental data, on the possibility of there being an anomalous gravitational acceleration of antimatter in quantum gravity scenarios. Up to now we have refrained from elucidating on this aspect partially because, as indicated in section 2.1, there is so much uncertainty in the nature of interactions of gravitational strength which may be appended to the standard model. This uncertainty even goes so far as to admit the possibility that one may need to abandon gauge invariance! Nonetheless, some cogent comments can be made.

Somewhat paradoxically, it turns out that the more precisely anomalous gravitational effects are ruled out in earth-based matter–matter experiments, the more unrestricted is the possibility that there can be a significant anomalous gravitational acceleration of antimatter. Explicit finite-ranged effects would restrict the parameters of new forces to match the data, and they could imply short ranges [Sta88]. However, with no measurable effects one could have the symmetry situation of an exact cancellation, even if the ranges are long. This would then produce strikingly apparent effects in antimatter experiments.

To begin, we expect that "new gravitational forces" would be a manifestation of some symmetry, perhaps of a space–time origin, which is broken in our world. The vector and scalar fields are presumed precisely to be symmetry partners of the graviton in any of the extended gravity scenarios. Thus, their couplings should be expected to be equal to those of the graviton up to symmetry-breaking effects. These in turn are expected to be small (second-order in gravity) and related to the symmetry breaking which would produce very small vector and scalar masses, with ranges as long as tens to hundreds of kilometers.

Thus, just as in the electroweak theory where the bosons split into the massless photon and approximately equally massive $W^{\pm}$ and Z^0 bosons (these massive bosons would be precisely degenerate if it were not for electromagnetic mixing effects), one can envision the theory to have a massless graviton and approximately equally massive vector and scalar particles. The question is, how good does the (broken) symmetry containing the vector and scalar remain?

At the simplest level, note that the potential of eqs. (2.1)–(2.3) would come from interaction Lagrangians of the form

$$\mathscr{L}_{\mathrm{V}} = a^{1/2} V_{\mu} J^{\mu} , \qquad \mathscr{L}_{\mathrm{S}} = b^{1/2} \phi T^{\mu}{}_{\mu} , \tag{8.1}$$

where V_{μ} is the vector field, J^{μ} is the baryon, lepton, or perhaps quark current to which it is coupled, ϕ is the scalar field, and $T^{\mu}{}_{\mu}$ is the trace of the energy–momentum tensor.

For normal materials, the integral of the trace of the energy–momentum tensor in units of atomic mass is equal to the baryon number to a fraction of 1 part in 10^3. (To put it simply, for ordinary matter any measure of the total mass is going to be proportional to baryon number to this accuracy). So, a priori we would expect that if the vector and scalar interactions were equal in strength then they would cancel (for matter) to at least this precision. Given the present inverse-square law tests, the ranges of these forces, if macroscopic, must also be approximately equal. For the sake of discussion take them to be 60 km. [From eq. (2.9) this corresponds to an anomalous antiproton acceleration of $0.02ag$.] Thus, in simplest approximation, in matter experiments these new forces would violate the principle of equivalence by less than the factor $10^{-5}a$ of normal gravity.

However, the experimental constraints on violations of the principle of equivalence are much stronger than this. Indeed, it has been argued that these experiments rule out the possibility of there being any observable effect in the antiproton gravity experiment (let alone ordinary matter experiments) to the level of $10^{-5}g$ [Ade90b] and even $2 \times 10^{-6}g$ [Ade91]. Although this is correct in simpler quantum gravity models, it is not the case from a more sophisticated viewpoint [Gold91c].

How can a very precise cancellation between the new vector and scalar gravitational forces postulated be implemented to satisfy the absence of any consistently observable effect in these experiments? To answer this question we will present an explicit type of model in which this result can be a straightforward consequence of the theory. Our point is not that this model is necessarily correct, but only that a model with such a property is viable.

To proceed, one must start by discussing how these new forces can couple in general to matter and energy. Begin with the vector force. As noted above, the gravivector is usually taken as coupled to some *conserved* charge, such as baryon or lepton number. However, because the gravivector is taken to be massive, there must be a breaking of the symmetry to which it is coupled; i.e., the corresponding charge *cannot be exactly conserved.*

But we know that both baryon and lepton numbers are conserved to a very high accuracy [PDG90]. Therefore, it is required that a coupling, even of gravitational strength, to a vector boson must either be to one that is very massive, or that some accident closes the channels for this decay [Gold80; GolA84].

An isolated U(1) symmetry factor can produce an exception to this generality because in that case it is possible to conserve the source current even if the (gauge) vector boson is massive. Thus, no discontinuity need appear, from increasingly large electric-charge nonconservation to exact electric-charge conservation, as the limit on the photon mass is made increasingly stringent down to zero [GolA71b; Davi75]. (Also see [Bart88; Pop91] for a related discussion on massive photon partners.)

Heretofore, it has been widely assumed that the gravivector must couple to a combination of baryon and lepton currents. The basis of that argument, however, has really been the question: what else is there? In brief, a lot!

Consider, for instance, the dilatation current

$$J^{\mu} = X_{\nu} T^{\mu\nu} , \tag{8.2}$$

which has the right dimensions to couple conventionally to the gravivector field. In a deSitter Universe, we may change $X_{\nu} \rightarrow \delta X_{\nu}$ locally and achieve a gravivector coupling source which, for slowly moving matter, is essentially identical to that for tensor gravity (and the simplest scalar coupling above). For the very large horizon, R_{H}, in our Universe, the deSitter violation of energy–momentum conservation is negligible. The value of the coupling of this current to the gravivector is more problematic. It might well be too small, of order $G_{\mathrm{N}}/R_{\mathrm{H}}^2$. In principle, however, such a current affords the opportunity for a gravivector source with an equivalence-principle-conserving strength.

Another possibility in string-based quantum gravity theories is that the gravivector couples to the "central charge," which counts the mode number in the compactified space attached to 4D spacetime. Since the degrees of freedom we see are "zero modes", one might at first think the coupling vanishes. However, quantum loops including higher modes will certainly induce an effective coupling of the gravivector to the zero modes also. This would still vanish if the zero modes were exactly massless, but they are not. The same symmetry breaking that produces ordinary mass scales will produce shifts of the higher-mode masses also. This in turn should prevent exact cancellation of the gravivector coupling to order $G_{\mathrm{N}}m^2$, where m is an ordinary mass scale. (The symmetry-breaking scale can also be expected to be related to the gravivector mass scale.) Here, prospects for gravitational-strength coupling and the mass dependence needed for precise cancellations are apparent, but the nature of the current is less clear.

Finally, we mention a very interesting current which couples to the bosonic degrees of freedom responsible for binding energy. This current is

$$J^{\mu} = \sum_{j} \epsilon^{\mu\nu\gamma\sigma} A_{\nu}^{j} \partial_{\gamma} A_{\sigma}^{j} , \tag{8.3}$$

which has the property of inducing a CP-violating coupling to the gravivector. Again, even assuming the gravivector does couple to baryon and lepton currents, the effect of this additional current can be such as to improve the cancellation between the gravivector and graviscalar effects on matter. Within the bounds of the discussion in section 7.2, we know of no data which exclude (finite-ranged) CP-violating interactions of gravitational strength. Here the question once more arises as to what exactly is the coupling strength. Is it G_{N} times m_{quark}^2, or G_{N} times the square of the average mass of the nucleon and delta, or G_{N} times what? In any event, this new current, combined with the standard vector-charged current, could yield an "effective vector coupling" to energy, allowing a precise cancellation of the normal scalar coupling in matter–matter interactions.

The above allows us the freedom to introduce new vector couplings, some of which would violate gauge invariance, such as

$$\delta\mathscr{L}_{\mathrm{V}} = a^{1/2} a_1 A_{\mu} V^{\nu} \partial^{\mu} A_{\nu} , \tag{8.4}$$

where A_{μ} is the photon field. Such a coupling is consistent with the observation that terms which are absent in standard gauge field theories, due to gauge-invariance considerations, arise very naturally in strong field theories [Kos91b]. But since these new couplings are not needed to make our point, we pass them by, having noted their possible existence.

Going on to the graviscalar field, it is similarly possible to modify its couplings to produce a better cancellation of even the "normal" vector coupling of eq. (8.1). As indicated in chapter 5, the scalar field may be expected to couple not only to the trace of the energy–momentum tensor but also to the square of the field-strength tensor for the gauge fields [Hill88; Hug89a, 90a],

$$\mathscr{L}_{\mathrm{S}} = b^{1/2}\phi T^{\mu}{}_{\mu} \rightarrow b^{1/2}\phi\Big(T^{\mu}{}_{\mu} + \sum_{j} \tfrac{1}{4} b_1{}^{j} F_j{}^{\mu\nu} F^{j}{}_{\mu\nu}\Big)\,. \tag{8.5}$$

For the new term, one must distinguish the $j = 0$ electromagnetic (or with an extension, the full electroweak) and $j = 1, \ldots, 8$ quantum chromodynamic (QCD) components.

Even though one must not forget our previous admonition about separating the total energy of a system into its rest mass and interaction-energy parts [Niet77], the electromagnetic part can be thought of as related to a measurement of the electromagnetic binding energy, $E_{\mathrm{b}}^{\mathrm{em}}$. This electromagnetic energy varies strongly from atom to atom as Z^2, but it is small compared to the electron mass (of order α_{em}^2).

The important thing, however, is that the total scalar potential energy due to this field on a hydrogen atom in this model is [Hug90a]

$$I = b(M_{\mathrm{p}} + m_{\mathrm{e}} - E_{\mathrm{b}}^{\mathrm{em}}/c^2 + 2b_1^0\langle F_{\mathrm{em}}^2\rangle)S\,, \tag{8.6}$$

where S is the scalar potential and

$$E_{\mathrm{b}}^{\mathrm{em}} = \int \mathrm{d}^3x\, T^{\mu}{}_{\mu} - (M_{\mathrm{p}} + m_{\mathrm{e}})/c^2\,, \tag{8.7}$$

$$\langle F_{\mathrm{em}}^2\rangle = \int \mathrm{d}^3x\, F_0{}^{\mu\nu} F^0{}_{\mu\nu}\,. \tag{8.8}$$

By the virial theorem (art. 34 of [Lan75] and [Lie81]) we have $\langle F_{\mathrm{em}}^2\rangle = -2E_{\mathrm{b}}^{\mathrm{em}}$ up to magnetic and relativistic corrections. Therefore, for $b_1^0 = -\frac{1}{4}$, one will have a scalar force which is proportional to the baryon and lepton numbers, in a particular combination, which could exactly cancel a vector force of appropriate coupling strengths to these particles with a precision by orders of magnitude higher than the claimed limit [Ade91]. For higher Z atoms the same conclusion still holds, with the neutrons just considered an electromagnetically free part of the system for now. Note that even if $b_1^0 = 0$, the scalar force is still effectively proportional to proton, neutron and lepton numbers, because the binding energy is relatively small (of order 1 part in 10^5 to 10^8).

The QCD part, which can be thought of as related to a measurement of the nuclear (chromodynamic) binding energy, $E_{\mathrm{b}}^{\mathrm{qcd}}$, varies almost exactly linearly with atomic number A, due to the saturation property of nuclear forces. Thus, this larger part, which nonetheless has a variation only of order one part in 10^3 of the total (rest mass) energy, also varies dominantly (approximately) proportional to baryon number. An argument similar to that of eqs. (8.6)–(8.8) can therefore be made for the QCD and QED gauge-field contributions to the total graviscalar potential energy of the nucleon. A generalized virial gives [Luc91]

$$\langle T\rangle = -\tfrac{1}{2}\langle V_{\mathrm{em}}\rangle + \tfrac{1}{2}\langle V_{\mathrm{qcd}}\rangle\,. \tag{8.9}$$

Therefore, tuning of the vector-quark couplings and the set of $\{b_1^j\}$, coupled with the knowledge of tracking of the chromomagnetic terms [Bely82; Gold88c], would allow better cancellation of the proton and neutron parts of the scalar and vector forces, even though the exact nature of the relativistic QCD virials remains an open question [Luc90].

As mentioned, the above use of virials shifts the effective scalar coupling to something more closely proportional to baryon and lepton number by the amount of the *electric* field strength contributions, because

$$F^{\mu\nu}F_{\mu\nu} \sim \boldsymbol{E}^2 - \boldsymbol{B}^2 . \tag{8.10}$$

Actually, of course, one obtains the *change* in this quantity between bound and non-interacting particles.

There is, however, another possibility which would allow for a very precise cancellation of all binding energy in the scalar coupling; namely coupling the graviscalar to

$$F^{\mu\nu}F^{\gamma\sigma}\epsilon_{\mu\nu\gamma\sigma} \sim \boldsymbol{E}^2 + \boldsymbol{B}^2 . \tag{8.11}$$

That is, at the cost of introducing *CP*-violation into the graviscalar interaction similar to that noted possible above for the gravivector, the effect of the graviscalar interaction may be significantly altered from the most naive expectation, namely that obtained from eq. (8.1).

Thus, considering all the terms contributing to this (generalized) gravitational interaction, one easily obtains dominant parts proportional either to baryon number and/or lepton number or else to energy. Therefore, it is not surprising that the vector and scalar pieces might be *expected* to cancel to high accuracy. (It is the undoing of this cancellation in gravitational antimatter experiments which makes them so critical for studies in this field.) As stated, unless the new forces are small because of small coupling strengths or very short ranges, the observations actually require a very precise cancellation.

Therefore, the importance of the Eötvös and Galileo principle of equivalence experiments lies not just in their implication of a needed approximate cancellation, which is almost automatic, but rather in their implication of a needed *precise* cancellation. This can be viewed either as being unnatural (in the technical sense) or occurring naturally as the result of some symmetry of the systems and their interactions.

In summary, we see that with some sophistication in the consideration of possible couplings, it is quite possible to imagine that graviscalars are effectively coupled very precisely to baryon (and lepton) number, or that gravivectors are effectively coupled very precisely proportional to the (time–time) component of the stress-energy tensor, or both. Our purpose is not to espouse any particular one of these possibilities, but rather to indicate the wide range that exists. From this, it should be clear that it is futile to attempt to rule out a precise cancellation using only matter in experiments. No firm prediction for an antimatter experiment can be made on such a basis.

However, this cancellation does not come without a "cost". In redshift experiments there is a new effect. In these experiments one must be concerned whether g_R, the acceleration due to gravity measured in the redshift, matches the value g_M, measured in matter experiments. That they could be different is due to the expected absence of a direct coupling of the gravitational vector field to gauge vector fields such as the photon. The term involving a has vanished but not, apparently, the term involving b, due to the scalar. However, the trace of the energy–momentum tensor for the photon also vanishes. Therefore, beyond the Einsteinian tensor contribution, the graviscalar could only contribute additionally to the redshift from its b_1 coupling to the square of the electromagnetic and chromodynamic field-strength tensors. For on-shell photons, this last also vanishes; i.e., the scalar and the vector are both fully decoupled from on-shell photons. (This is to be differentiated from the fundamental scalar interaction causing *massive* clocks to emit photons of different frequencies [Cran88; Hug89a, 90a].)

Since, in this scenario, the vector contribution cancels the scalar contribution for any matter in the clocks, the total contribution to the redshift of photons as interpreted in terms of differing clock rates is of the form

$$c^2(\Delta\omega/\omega) = \Delta T + 2nb_1 b(\langle F_{\text{tot}}^2\rangle / M_{\text{tot}})\,\Delta S\,, \tag{8.12}$$

where T is the Newtonian potential, M_{tot} is the total mass of the relevant constituents of the clock, and n, of order unity, varies among clocks using different electromagnetic processes [Hug89a, 90a]. Equation (8.7) agrees with the general consideration [Unr79] that in linear approximation one has a redshift, or rescaling of time, that goes as $1 + P/c^2$, where P is a (total) gravitational potential.

From our previous discussion we saw that the contribution of the b_1 term in eq. (8.7) need not be larger than 1 part in 10^3 to account for the precise cancellations of vector and scalar contributions in those experiments since $\langle F_{\text{tot}}^2\rangle / M_{\text{tot}} \sim 10^{-3}$. (Recall that there is great uncertainty in this estimate because at this level one is unsure of the precise nature of the gravitational vector-coupling strength variation with substance.) There is a further reduction because the finite range of S means $\Delta S/\Delta T \sim 0.01$. Thus, the difference between g_{R} and g_{M} would not be expected to appear above the level of one part in 10^5.

Since gravitational-redshift experiments have not yet reached this accuracy on longer-range scales [Kri90b], they do not yet provide any significant constraints. Nonetheless, it is clear that redshift measurements have a significant potential for shedding light on these questions. (We return to these points in the next section.)

In addition to this "cost" of predictions of differences in the redshift measured between clocks and photons (or other types of clocks), there may be *CP*-violating effects, associated with the *CP*-violating interactions suggested above. These may appear, for example, as a difference in redshift between photons of differing polarizations. We will discuss this in detail elsewhere [Niet91b].

It is clear, however, that the suggestion, even made in very general terms, that the gravivector and graviscalar effects cancel very precisely in gravitational experiments with matter, is *not* devoid of content. Several additional tests involving relative redshifts and *CP*-violating effects immediately present themselves as possibilities. Although these may all independently have strong motivation, none, however, is as direct, clean and conclusive a test of the gravitational properties of antimatter as the direct measurement of its acceleration in the gravitational field of the earth.

8.2. Critical experiments for longer-ranged forces

The preceding discussion shows that completed experiments cast doubt on their being significant new gravitational forces with ranges on the order of 1–1000 m. However, the regime of 1–100 km remains open. As such, we find that there are three experiments which are critical [Niet91a].

(i) *Boynton's experiment at the Palisades site* [Boy90]. No fault has been found with Thieberger's experiment at the Palisades site. Of all the sites used for principle of equivalence experiments, this is the one with the clearest large-scale geologic feature. If there are (approximately cancelling) longer-ranged, new gravitational forces extant, then this could explain Thieberger's positive result where others find a null result. If a separate experiment finds or does not find an effect at this site, this would significantly impact the viability of the proposition that there are longer-ranged, new gravitational forces that violate the principle of equivalence.

(ii) *The ocean big-G experiment* [Hil88]. The Greenland experiment reported an anomalous signal. Although in principle the signal could have been taken as evidence for a violation of the inverse-square law, in fact it was realized that the signal also could have been due to unknown geology in the bedrock. The ocean experiment will be much better able to determine whether or not there is a violation of the inverse-square law, because it has measured gravity on planes at the surface and at depth. However, the ocean experiment would not determine the parameters of new forces as well as a similar land experiment could, because of the errors involved in taking measurements in a nonstatic ocean. If an effect is seen in the ocean experiment, then that would be strong motivation to do a deep-ice experiment in Antarctica. With respect to the existence of new, longer-ranged forces, these three geophysical experiments would then be in the pattern of indicating (a) maybe, (b) yes or no; and if yes, then (c) what the values of the parameters are.

Further, a positive result from the ocean experiment would stimulate interest in spacecraft experiments of the type discussed in section 3.5. These could test interactions in the 10–100 km range [Wil89b].

(iii) *The antiproton gravity experiment* [Bro86, 91; Jar87; Dye89; Holt90; Holz91]. If critical experiments (i) and (ii) yield null results, this experiment (iii) could still see an effect because, as noted in section 2.2, it measures $|a + b|$. This experiment would at least be important in limiting the size of effects from longer-ranged (of order 10 to 100 km), new gravitational forces.

A good test for shorter-ranged ($<$1–10 km) gravitational forces using antimatter is beyond the scope of the present antiproton experiment. One would need a sensitivity on the order of 100 times greater, since the strength of an anomalous effect on the surface of the earth would vary approximately as the range of the interaction [Niet88c]. Such a test will remain for future experiments, perhaps using antihydrogen [Gold87; Ric87; Gab88a; Niet88b].

(iv) *Low-orbit redshift experiments*. As explained in the last section, if there were null results in matter–matter experiments and yet anomalous results from antimatter–matter experiments, this would imply anomalous results in redshift experiments. Under these conditions, the anomalies would result from forces with ranges on the order of 100 km.

One could search for such anomalies by sending atomic clocks into eccentric orbits around the earth. Indeed, Smarr, Vessot and collaborators have proposed this type of experiment, but with a much larger orbital semimajor axis (4.22×10^7 km) [Sma83]. Even their experiment would not be simple. For the low-altitude orbit necessary to test 100 km ranges, tracking problems would make it even harder to obtain a precise result. Note, however, that a low orbit about the moon would be easy to maintain and track because of the lack of an atmosphere.

(v) *Neutral-kaon experiments*. For an intuitive measure of gravitational effects on neutral kaons, in section 7.2 we showed how an anomalous tensor interaction on antimatter (i.e., "antigravity") could produce a relative phase shift between the matter and antimatter components of the neutral kaon system. The magnitude of this phase shift approaches being measurable as an anomalous regeneration of K_S mesons. But independently of this, both vertical- and horizontal-beam experiments would be useful, because the internal matter and antimatter components of the two neutral kaons complicate the analysis of the effects of new gravitational forces [Gold91a]. To be more specific, because the neutral kaons are both composed of a quark and an antiquark of different types, these experiments would provide complementary information to that from the previous two critical experiments.

8.3. Antiproton gravity and the principle of equivalence

We emphasize once again that, independently of the motivation from quantum gravity, this experiment would open up a whole new area for tests of general relativity – that of antimatter. Whatever the result of this experiment, it would indeed be a classic.

Independently of whether or not the binding energy in a particular system comes from the existence of antimatter in the virtual fields, the discussion here has emphasized that it is important to look to experiment to try to limit the theoretical possibilities. Some statements can be made in a model-independent way but others can only be made in a model-dependent way. One must be careful to distinguish the two. In general only model-dependent statements are correct even though one is tempted to assume the statements are model-independent [Stu88].

Finally, and most importantly, we reiterate (see section 8.1) that, as the bounds on $|a - b|$ are tightened by experiments, *the bound on the possible size of apparent violation of the weak principle of equivalence* ($|a + b|$) *for antimatter may be loosened.* This can occur because, if the gravivector and graviscalar forces could cancel exactly, there could be no observable effect in matter–matter interactions, either by violations of the weak principle of equivalence or of the inverse-square law. Thus, somewhat paradoxically, the common range of these new gravitational forces becomes less constrained as the precision of their cancellation for matter–matter interactions improves. Of course, the observed effect on antimatter grows as this range increases as does the anomaly in redshift experiments.

In conclusion whether or not one now accepts the existence of non-Newtonian gravitational forces, the possibility of new non-inverse-square and/or composition-dependent components of gravity must be thoroughly studied. In this respect the antiproton experiment offers the advantage of a potentially large signal, and is a test of fundamental importance.

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