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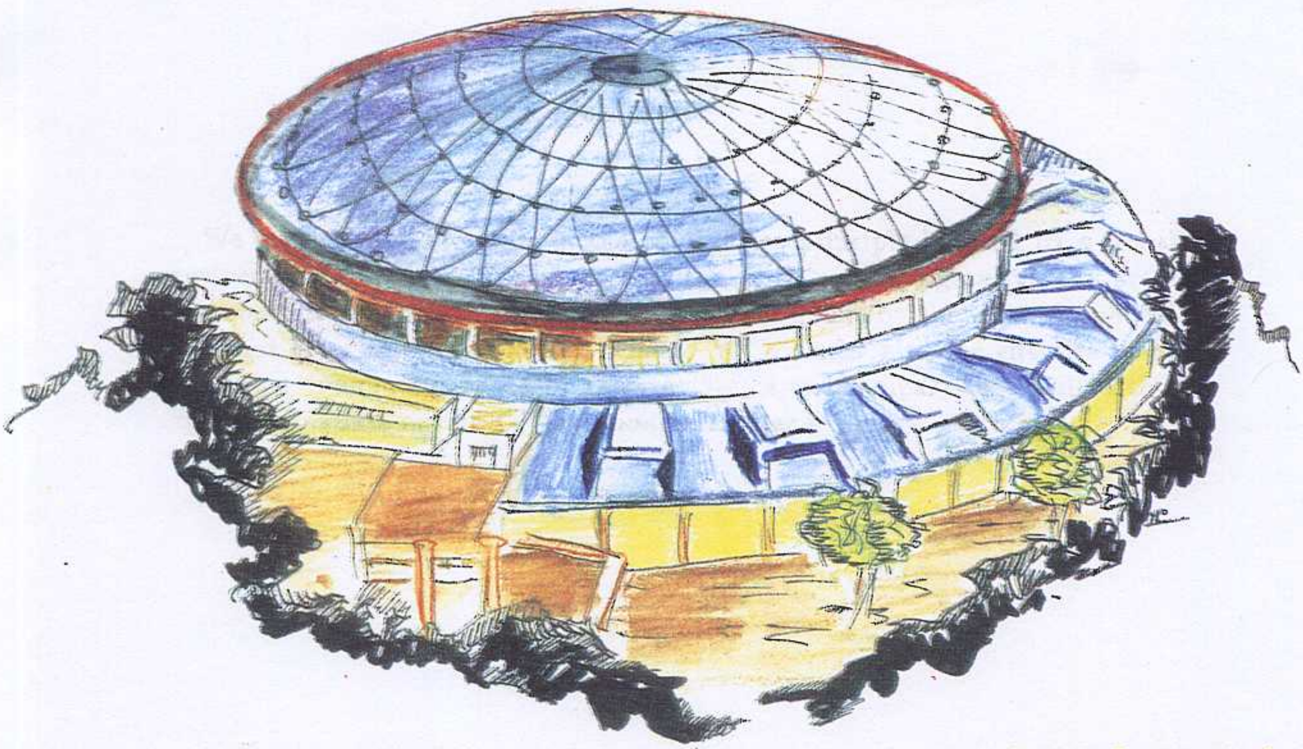

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The equivalence principle, CP violations and the Higgs boson mass

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Abstract

We consider the violation of the equivalence principle induced by a massive gravivector, i.e. the partner of the graviton in $N > 1$ supergravity. The present limits on this violation allow us to obtain a lower bound on the *v.e.v.* of the scalar field that gives the gravivector its mass. We consider also the effective neutral kaon mass difference induced by the gravivector and compare the result with the experimental data on the CP violation parameter ϵ.

1 Introduction

In the recent times there has been a renewed interest in the topic of antigravity [1]. This interest is prompted by the PS–200 experiment proposed at the Low Energy Antiproton Ring (LEAR) at CERN for the high precision measurement of the difference between the gravitational masses of the proton and antiproton [2], as well as by the possibility that the so called Morrison's antigravity [3] may be responsible for the measured CP violations [4]. However, the kind of antigravity proposed by Morrison was excluded in early work by Schiff [5] on the grounds of the limits set by the Eötvös experiment on the atom accelerations in the field of the earth. Schiff's calculation was found inconclusive in the review article by Nieto and Goldman [1]. In any case, it appears very problematic, to say the least, to extend Morrison's concept of antigravity to the case of relativistic particles.

A more clearly motivated theoretical framework for antigravity emerges from the work of Scherk [6], [7]. As he pointed out, the $N = 2, ..., 8$ theories of supergravity lead to antigravity. In his work it was also shown that this kind of antigravity is not excluded by the Eötvös experiment. As an important consequence of the limits set by this experiment, the spin 1 supersymmetric partner of the graviton considered by Scherk must necessarily have a nonvanishing mass.

It should be recalled that the $N > 1$ supersymmetric models suffer from the well known difficulty in the introduction of the fermion chirality, hence the case $N = 1$ is phenomenologically more viable in providing a unified description of the theory of the elementary particles and gravity [8]. This case emerges also in the context of superstring theory [9]. In spite of this difficulty, it is of interest to reconsider the implications of the supergravity argument for antigravity.

We follow Scherk in introducing the antigravity due to the gravivector field. As a result of its acquiring a mass through the nonzero *v.e.v.* of one of the scalar fields in the theory, its Compton wavelength becomes related to a possible violation of the equivalence principle. In this letter, we show how this correspondence works in detail and how the currently available experimental limits on the violation of the equivalence principle can be used to set a bound on the *v.e.v.* of the scalar field that gives a mass to the gravivector.

Moreover, considering the K^0-$\overline{K}^0$ system in the gravivector static field of the earth, Scherk calculated the effective mass difference $m_{K^0} - m_{\overline{K}^0}$ [7]. We review this calculation and compare it with the results of the CP violation experiments. This yields a limit on the Compton wavelength of the gravivector which is less stringent than the one obtained from the tests of the equivalence principle.

This letter is organized as follows. In the next section we derive the limits on the Compton wavelength of the gravivector and the *v.e.v.* of the scalar field, using high precision tests of the equivalence principle. Section 3 describes the effect of the gravivector field in the K^0-$\overline{K}^0$ system and compares the result with the measured CP violation parameters. The conclusions are drawn in sec. 4.

2 Bounds from tests of the equivalence principle

Let us consider the coupling of the gravivector A^l_μ to the fields of the matter scalar multiplet, which occurs through the coupling to a conserved $U(1)$ current [6], [7]

$$j^l_\mu = k(m_u \bar{\chi}_u \gamma_\mu \chi_u + m_d \bar{\chi}_d \gamma_\mu \chi_d) \; , \tag{2.1}$$

where $k^2 = 4\pi G$, m_u and m_d are the up and down quark masses, respectively, and $\chi_{(i)}$ are Dirac spinors. The strength of the coupling has the form [10]

$$g_i = \pm k\, m_i \tag{2.2}$$

for $N = 2$, and [11], [12]

$$g_i = \pm 2k\, m_i \tag{2.3}$$

for $N = 8$, where m_i are the quark and lepton masses. In eqs. (2.2), (2.3) the positive (negative) sign holds for (anti)particles and $g = 0$ for self–conjugated particles. The graviton couples to the real mass of the nucleon, whereas its vector partner couples only to the masses of the individual particles constituting the nucleon which are not self–conjugated. As a result, one has the potential for the interaction between the earth and the atom (Z, A) (where Z and A are the atomic and mass number, respectively) [6]

$$V = -\frac{G}{r}\left[M M_\oplus - \eta M^0 M^0_\oplus f\left(\frac{R_\oplus}{R_l}\right)\exp(-r/R_l)\right] \; , \tag{2.4}$$

$$\eta = \begin{cases} 1 & , \quad N = 2 \\ 4 & , \quad N = 8 \end{cases} \tag{2.5}$$

where R_l is the Compton wavelength of the gravivector, and $R_\oplus = 6.38 \cdot 10^6$ m, $M_\oplus = 5.98 \cdot 10^{24}$ kg are the earth radius and mass, respectively. The function

$$f(x) = 3\,\frac{x\cosh x - \sinh x}{x^3} \tag{2.6}$$

takes into account the so called skin effect for a spherical homogeneous distribution of the point sources of the Yukawa potential, i.e. the fact that the sources cannot be taken to be at the center of the sphere, as in the case of the Coulomb potential. Moreover

$$M = Z(M_p + m_e) + (A - Z)M_n \; , \tag{2.7}$$
$$M^0 = Z(2m_u + m_d + m_e) + (A - Z)(m_u + 2m_d) \; , \tag{2.8}$$

where M_p, M_n and m_e are the proton, neutron and electron masses, respectively. Introducing an average atom $(Z_\oplus, A_\oplus)$ with $A_\oplus \simeq 2Z_\oplus$, we obtain from eqs. (2.7), (2.8)

$$M^0_\oplus \simeq \frac{3m_u + 3m_d + m_e}{M_p + M_n}\, M_\oplus \; . \tag{2.9}$$

We consider the case in which one of the matter (scalar) fields has a nonzero vacuum expectation value $\langle\phi\rangle$, as in the case of the Higgs field ϕ that breaks $SU(2) \times U(1)$ down to $U(1)$. This yields a mass for the A^l_μ field [1]

$$m_l = \frac{1}{R_l} = k\, m_\phi \langle\phi\rangle \,. \tag{2.10}$$

In this case, eq. (2.4) implies that the equivalence principle is violated. In fact, the difference between the accelerations of two atoms with numbers (Z, A) and (Z', A') in the field of the earth can be derived from the potential for gravity plus antigravity:

$$V(r) = -\frac{GM_\oplus}{r}\left[M - \eta\,\frac{3m_u + 3m_d + m_e}{M_p + M_n}\, M^0 f\left(\frac{R_\oplus}{R_l}\right) \exp(-r/R_l)\right] \,. \tag{2.11}$$

The result is

$$\frac{\delta\gamma}{\gamma} = \eta\,\frac{(3m_u + 3m_d + m_e)(m_e + m_u - m_d)}{M_n\,(M_p + M_n)}\left(\frac{Z'}{A'} - \frac{Z}{A}\right) f\left(\frac{R_\oplus}{R_l}\right)\left(1 + \frac{R_\oplus}{R_l}\right)\exp(-R_\oplus/R_l) \,. \tag{2.12}$$

The Eötvös experiment at the University of Washington [13] (hereafter "Eöt–Wash") tested the equivalence principle in the field of the earth for berillium ($Z = 4$, $A = 9.0$) and copper ($Z' = 29$, $A' = 63.5$), and produced the limit

$$\left|\frac{\delta\gamma}{\gamma}\right| < 10^{-11} \,. \tag{2.13}$$

Equation (2.12) gives a representation of $|\delta\gamma/\gamma|$ as an increasing function of R_l; hence (2.13) provides an upper limit on the value of R_l:

$$R_l < 34\,\eta^{-1} \text{ m} \,, \tag{2.14}$$

which corresponds to the limit on the gravivector mass

$$m_l > 6 \cdot 10^{-18}\,\eta \text{ GeV} \,. \tag{2.15}$$

The light quark masses we choose, i.e. $m_u = 5.6$ MeV, $m_d = 9.9$ MeV, are obtained using chiral symmetry and the measured pion and kaon masses [14]. The masses entering the QCD Lagrangian depend on the energy scale and the renormalization scheme. The above selected values of m_u and m_d are adequate for our purpose of giving an order of magnitude estimate of the effect of antigravity. These values hold for the so–called current quark masses at 1 GeV, and are very close to the average values of the ranges suggested in ref. [15] to account for the variations due to the above mentioned uncertainties:

[1] The case when A^l_μ describes a massless field has been ruled out by Scherk [6] on the basis of the Eötvös experiment.

$$2 \text{ MeV} \le m_u \le 8 \text{ MeV} , \tag{2.16}$$

$$5 \text{ MeV} \le m_d \le 15 \text{ MeV} , \tag{2.17}$$

$$0.25 \le \frac{m_u}{m_d} \le 0.70 . \tag{2.18}$$

Thus, the high precision in the test of the equivalence principle provided by the Eöt–Wash experiment yields the lower bound on the mass of the Higgs boson

$$m_\phi \simeq \langle \phi \rangle > 5\,\eta^{1/2} \text{ GeV} . \tag{2.19}$$

A similar limit on the scalar field mass is obtained for the Eöt–Wash experiment performed using berillium and aluminum [13].

The higher precision $|\delta\gamma/\gamma| < 10^{-12}$ for platinum ($Z = 78$, $A = 195.1$) and aluminum ($Z' = 13$, $A' = 27.0$) of the Moscow experiment [16] does not allow us to obtain a more stringent limit on m_ϕ, due to the fact that eq. (2.12) has to be replaced by

$$\frac{\delta\gamma}{\gamma} = \eta \, \frac{(2m_u + m_d + m_e)(m_e + m_u - m_d)}{M_n \, M_p} \left(\frac{Z'}{A'} - \frac{Z}{A} \right) f\left(\frac{R_\odot}{R_l} \right) \left(1 + \frac{R_{AU}}{R_l} \right) \exp(-R_{AU}/R_l) \, , \tag{2.20}$$

where $R_\odot = 7 \cdot 10^8$ m is the sun radius and $R_{AU} = 1.5 \cdot 10^{11}$ m is the astronomical unit. Here we assume that the sun is composed of hydrogen ($Z_\odot = A_\odot = 1$). There are important differences in eq. (2.20) with respect to eq. (2.12). In the former equation the two distance parameters $R_\odot$, R_{AU} – both much larger than $R_\oplus$ – enter, whereas in the latter equation only the length scale $R_\oplus$ appears. What really matters is the tiny size of the factor $\exp(-R_{AU}/R_l)$ in the right hand side of eq. (3.1). This damps the effect on R_l of the improvement on the precision of the limit $|\delta\gamma/\gamma|$ obtained in the Moscow experiment. As a consequence, the upper bound on R_l is changed to

$$R_l \begin{cases} < 8 \cdot 10^9 \text{ m} , & N = 2 \\ < 7 \cdot 10^9 \text{ m} , & N = 8 \end{cases} \tag{2.21}$$

corresponding to

$$m_l \begin{cases} > 2 \cdot 10^{-17} \text{ eV} , & N = 2 \\ > 3 \cdot 10^{-17} \text{ eV} , & N = 8 . \end{cases} \tag{2.22}$$

This provides us with the limit $m_\phi > 0.3$ MeV, which is clearly not interesting. The other experiments that are tests of the equivalence principle quoted in the review paper by Will [17] provide less stringent limits on R_l and m_ϕ.

It appears that Scherk missed the correct equation (2.20). Instead, he incorrectly used eq. (2.12) and obtained a 2 m upper bound on R_l from the $|\delta\gamma/\gamma| < 10^{-11}$ limit determined by the Princeton experiment [18]. Therefore, from this equation Scherk could have obtained only the much less stringent limit (three orders of magnitude higher)

$$R_l < 2.5 \cdot 10^3 \, \eta^{-1} \quad \text{m} \tag{2.23}$$

coming from the Eötvös experiment [19], where we have the limit $|\delta\gamma/\gamma| < 5 \cdot 10^{-9}$ for platinum and magnalium, whose composition is 90% aluminum and 10 % magnesium ($Z = 12$, $A = 24.3$).

For the sake of comparison, we consider also the upper bounds on R_l coming from the Princeton experimental limit. Since this experiment was carried out in the sun field we have to resort to eq. (2.20), which yields for aluminum and gold ($Z = 79$, $A = 197.0$)

$$R_l \begin{cases} < 9 \cdot 10^9 \text{ m} & , \quad N = 2 \\ < 8 \cdot 10^9 \text{ m} & , \quad N = 8 \,. \end{cases} \tag{2.24}$$

This bound is much worse than the one in eq. (2.23) and can be discarded.

Finally, in the spontaneously broken $N = 8$ supergravity [11], [12], a graviscalar appears together with the gravivector that we have considered, and so it is natural to ask if the former contributes to $\delta\gamma/\gamma$, hence to a possible violation of the equivalence principle. However, it is immediately seen that this is not the case, since this contribution has the same sign for both matter and antimatter and thus cancels in $\delta\gamma$.

3 Comparison with *CP* violation experiments

In the previous section we have seen how the limits obtained in the Eöt–Wash experiment for the equivalence principle in the field of the earth affect the Compton wavelength of the gravivector. The measured values of the neutral kaon mass difference $\Delta m_K \equiv m_{K_L} - m_{K_S}$ and the *CP* violation parameter ϵ may also be used in order to obtain an upper limit on R_l. Here we follow Scherk [7] and calculate the effective mass difference between the K^0 and $\overline{K}^0$ due to their coupling to the gravivector field generated by the earth. Recalling that the earth acts as a source made almost entirely of matter (and no antimatter) and taking the static limit, yields the result [7]

$$\left| m_{K^0} - m_{\overline{K}^0} \right| = \frac{12\pi G}{c^2 R_\oplus^3} \eta M_\oplus^0 \left(m_s - m_d \right) R_l^2 \,, \tag{3.1}$$

where c is the speed of light and we used the fact that $R_l << R_\oplus$, according to the upper bound (2.14), in order to approximate the function $f(x)$ of eq. (2.6) by

$$f(x) \simeq \frac{3}{2x^2} e^x \quad , \quad x >> 1 \,. \tag{3.2}$$

Here we take the current quark mass $m_s = 199$ MeV at the 1 GeV energy scale [14].

A rough upper limit on the left hand side of eq. (3.1) can be derived from the measured values of ϵ and Δm_K [15]:

$$\left| m_{K^0} - m_{\overline{K}^0} \right| \leq \epsilon \, \Delta m_K \,. \tag{3.3}$$

This yields, recalling eq. (3.1)

$$R_l \leq c R_\oplus \left(\frac{R_\oplus}{12\pi G \eta M_\oplus^0} \frac{\epsilon \, \Delta m_K}{m_s - m_d} \right)^{1/2} = 1.6 \cdot 10^3 \, \eta^{-1/2} \quad \text{m} \,. \tag{3.4}$$

This bound is much less stringent than the one in (2.14) and has the same order of magnitude as the limit obtained by Scherk [2], i.e. $R_l \leq 8 \cdot 10^2$ m.

Thus, it is possible for us to discard the limit on R_l coming from the measured size of CP violations with respect to the bound provided by the tests of the equivalence principle since we are using the high precision limits of the Eöt–Wash experiment, which were not available to Scherk. Instead, he should have retained the constraint introduced by the coupling of the gravivector to the K^0–$\overline{K}^0$ system since this provides a better limit than (2.23) on the Compton wavelength of the gravivector.

4 Conclusions

The physical implications of the vector partner of the graviton field we studied can be considered as tests of the $N \geq 2$ locally supersymmetric theories where this particle is advocated. These tests are particularly relevant since they determine bounds on some of the physical parameters of the model. In particular, the massive field of the gravivector can in principle mediate a long range force. Other distinctive features of the theory include particles such as the gluinos and the gravitinos which, on the contrary, cannot contribute to long range forces. Hence, the effect of the gravivector can be detected in experiments searching for violations of the equivalence principles and deviations from Newton's inverse square law.

The experimental limits on the violations of the equivalence principle set an upper bound of order 10 m on the Compton wavelength of the gravivector. In turn, this allows us to constrain the *v.e.v.* of the scalar field that provides a mass for the gravivector to be of order 10 GeV or higher. The best way to improve these bounds is to push the limit on $|\delta\gamma/\gamma|$ in the earth field. The tests of the equivalence principle carried out using the sun as the gravitational field source cannot improve the limits on the physical parameters of the $N \geq 2$ supergravity theories considered here.

The gravivector field of the earth introduces a deviation from Newton's law which can be described by defining the effective gravitational "constant" [7]

$$G_{eff}(r) = G\left[1 + \alpha\left(1 + \frac{r}{R_l}\right)\exp(-\frac{r}{R_l})\right] , \tag{4.1}$$

$$\alpha = \eta \frac{M^0 M^{0\prime}}{MM'} . \tag{4.2}$$

[2] The loose agreement of (3.4) with Scherk's result is due to the use he made of approximated values for $M^0_\oplus$ and $m_s - m_d$ which differ from ours.

For experiments in the earth field, according to eq. (2.9)

$$\frac{M^{0\prime}}{M'} \equiv \frac{M^0_\oplus}{M_\oplus} = 0.025 \ . \tag{4.3}$$

This corresponds roughly to a value of α of order 10^{-3}–10^{-4} depending on M^0/M, i.e. on the composition of the test body. In order to improve the present limit on the range of the gravivector in (2.14), the experiments aimed to detect the possible deviations from Newton's law must be precise enough to set a limit of at least 10^{-3} on the value of α measured on length scale of 10 m or less.

An independent test could come from the CP violation experiments. Here the interaction with the static gravivector field generated by the earth produces an effective mass difference between the K^0 and the $\overline{K^0}$. What is measured is an upper bound for this mass difference given by the product of the CP violation parameter ϵ and the K_L–K_S mass difference. It turns out that the size of the observed CP violations is too large to provide a significant constraint on the mass of the gravivector.

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