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Confronting Dilaton-exchange gravity with experiments

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Abstract

We study the experimental constraints on theories, where the equivalence principle is violated by dilaton-exchange contributions to the usual graviton-exchange gravity. We point out that in this case it is not possible to have any CPT violation and hence there is no constraint from the CPT violating measurements in the $K-$system. The most stringent bound is obtained from the $K_L - K_S$ mass difference. In contrast, neither neutrino oscillation experiments nor neutrinoless double beta decay imply significant constraints.

At present we have no indication for the the violation of gravitational laws. But some theories like string theory suggest deviations from the usual graviton-exchange theories of gravity. Thus it becomes neccessary to find out the extent of applicability of the general theory of relativity. Several experiments were performed to test the equivalence principle [1] for ordinary matter and to test local Lorentz invariance [2, 3]. Attempts were also made to test these laws in the neutrino sector [4, 5, 6], but these works included only tensorial interactions. In the K-system both tensorial and vectorial interactions were studied by many authors [7].

Recently it has been suggested [8] that string theory may lead to a different kind of violation of the equivalence principle (VEP) via interactions of the dilaton field, which gives an additional contribution to the usual graviton exchange gravity. The resulting theory is of scalar-tensor type (in contrast to purely tensorial VEP discussed previously) with the two particle static gravitational energy

$$V(r) = -G_N m_A m_B (1 + \alpha_A \alpha_B)/r, \tag{1}$$

where G_N is Newton's gravitational constant and α_j are the couplings of the dilaton field ϕ to the matter field of type j, ψ_j. This additional contribution may result from a gravitational interaction

$$L = m_j \alpha_j \overline{\psi_j} \psi_j \phi. \tag{2}$$

The distinct feature of this new contribution are specific couplings of the dilaton field to different matter fields, which violates the equivalence principle. It has been discussed recently whether this feature can be tested in neutrino oscillation experiments [9, 10].

Unlike the violation of the equivalence principle through tensorial interactions, in the dilaton-exchange gravity the gravitational basis is always the same as the mass basis, since the additional term due to dilaton exchange is directly proportional to the mass. For this reason, a dilaton-exchange gravity cannot explain the neutrino mixing phenomenon by itself – the discussion in ref [9] seems to overlook this point. However, it is possible that a mass difference between degenerate neutrinos is implied, what has been considered in [9]. In this article we discuss constraints on this additional contribution from the $K_L - K_S$ mass difference, the non-observation of neutrinoless double beta decay as well as neutrino oscillation experiments.

In a linearized classical theory one may replace the effective mass of a fermion by

$$m_i^* = m_i - m_i \alpha_i \phi_c \tag{3}$$

where ϕ_c is the classical value of the dilaton field and is proportional to the Newtonian potential ϕ_N,

$$\phi_c = \alpha_{ext} \phi_N.$$

The first term results from the usual graviton-exchange gravity, while the second term is the new contribution coming from the dilaton-exchange gravity.

To get the interaction of the usual neutrinos of different flavour, we can rotate the effective hamiltonian in the mass and the gravitational bases through the same unitary rotations

$$H_w = U(H_m + H_g)U^{-1}. \tag{4}$$

In presence of the dilaton-exchange gravity, the effective hamiltonian in the mass basis is

$$H_m + H_g = pI + \frac{1}{2p}\begin{pmatrix} m_1 - \alpha_1 m_1 \phi_c & 0 \\ 0 & m_2 - \alpha_2 m_2 \phi_c \end{pmatrix}^2. \tag{5}$$

Here p denotes the momentum, I represents an unit matrix, and for any quantity X we define $\delta X = (X_1 - X_2)$ and $\bar{X} = (X_1 + X_2)/2$.

Assuming there is no CP violation, the effective hamiltonian becomes real and symmetric and we can parametrize the mixing matrix by

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \tag{6}$$

where θ is the mixing angle. Then the effective hamiltonian in the weak basis becomes

$$H_w = pI + \frac{1}{2p}\begin{pmatrix} M_+ & M_{12} \\ M_{12} & M_- \end{pmatrix}^2 \tag{7}$$

with

$$\begin{aligned} M_\pm &= \bar{m} + \frac{1}{2}(\alpha_1 m_1 + \alpha_2 m_2)\phi_c \pm \frac{1}{2}[\delta m + (\alpha_1 m_1 - \alpha_2 m_2)\phi_c]\cos 2\theta \\ M_{12} &= -\frac{1}{2}[\delta m + (\alpha_1 m_1 - \alpha_2 m_2)\phi_c]\cos 2\theta. \end{aligned} \tag{8}$$

The mass squared difference between the physical masses is given by

$$\Delta m^{*2} = \Delta m^2 - 2\phi_c(\alpha_2 m_2^2 - \alpha_1 m_1^2) + \phi_c^2(\alpha_2^2 m_2^2 - \alpha_1^2 m_1^2), \tag{9}$$

while the mass difference is given by

$$m_2^* - m_1^* = \delta m + (\alpha_2 m_2 - \alpha_1 m_1)\phi_c. \tag{10}$$

We shall now use the above formalism to analyse the constraints on dilaton-induced gravity from the $K_L - K_S$ mass difference, neutrinoless double beta decay and neutrino oscillation experiments. For the $K-$system, the physical states are the K_L and K_S states, while the weak states are the K° and $\overline{K^\circ}$ states. Thus the $K_L - K_S$ mass difference can be read off from equation [10],

$$m_L^* - m_S^* = (m_L - m_S) - m_L \phi_c(\alpha_L - \frac{m_S}{m_L}\alpha_S). \tag{11}$$

The experimental value $m_L^* - m_S^*$ is dominated by the mass difference $m_L - m_S$. Thus no significant cancellations are expected and a conservative bound for the contribution from dilaton exchange is

$$|m_L \phi_c(\alpha_L - \frac{m_S}{m_L}\alpha_S)| < m_L^* - m_S^*.$$

Using also $m_S \simeq m_L$ this implies a bound on the dilaton-induced gravity coupling of

$$\delta\alpha < \frac{1}{\phi_c}\left(\frac{m_L - m_S}{m_L}\right)_{expt} = \frac{7 \times 10^{-15}}{\phi_c}, \tag{12}$$

where we used $\frac{m_L - m_S}{m_L} \sim 7 \times 10^{-15}$ [11]. While the bound depends on the absolute value of ϕ_c, we can obtain a rough estimate by considering the value of the Newtonian gravitational potential to be due to the great attractor, which is about 3×10^{-5} and $\alpha_{ext} \sim 0.03$, so that $\phi_c \sim 10^{-6}$. Then the bound becomes $\delta\alpha < 7 \times 10^{-9}$.

Unlike for the tensorial interactions, in this case the measurement of the CPT violating parameter, the mass difference of K° and $\overline{K^\circ}$, does not yield any constraint. This can be understood by considering the mass difference, which can be read off from equation (8) to be

$$M_+ - M_- = \delta m \cos 2\theta + \phi_c \cos 2\theta(\alpha_2 m_2 - \alpha_1 m_1). \tag{13}$$

Here the first contribution is the usual mass contribution and the second contribution is the one coming from dilaton exchange. Since there is no CPT violation in the usual gravity, we have $\cos 2\theta = 0$. This implies that there is no contribution coming from the dilaton exchange gravity.

We now turn over to discuss the constraints coming from the neutrino sector. The decay rate for neutrinoless double beta decay is given by,

$$[T_{1/2}^{0\nu\beta\beta}]^{-1} = \frac{M_+^2}{m_e^2} G_{01}|ME|^2, \tag{14}$$

where ME denotes the nuclear matrix element $ME = M_F - M_{GT}$, (for numerical values see [12]), G_{01} corresponds to the phase space factor defined in [13] and m_e is the electron mass. In contrast to the tensorial VEP [6] for dilaton exchange gravity the observable has no explicit momentum dependence. The contribution of the dilaton exchange to the observable for neutrinoless double beta decay is given by

$$M_{+dil} = \frac{1}{2} m_2 \phi_c [(\frac{m_1}{m_2}\alpha_1 + \alpha_2) + (\frac{m_1}{m_2}\alpha_1 - \alpha_2)\cos 2\theta]. \tag{15}$$

Since no momenta enter the observable, the decay rate is suppressed considerably (see also the discussion in [14], which critizizes the treatment in [15]).

The dominant contribution to the neutrino oscillations comes through the change in the mass squared difference, given by

$$< \Delta m^2 >_{dil} = -2\phi_c m_2^2 (\alpha_2 - \frac{m_2^2}{m_1^2}\alpha_1). \tag{16}$$

In the almost degenerate case the bounds from the two experiments can be compared if we assume that there is no mean deviation of usual gravity $(\alpha_1 + \alpha_2) = 0$, which is assumed in most cases. An alternative natural choice is to assume that the masses of the neutrinos are hierarchical to explain the atmospheric and solar neutrino problems. In the case of hierarchical neutrino masses, $m_2 \gg m_1$, α_1 drops out from both expressions and without any further assumption all experiments can be compared in terms of the single unknown parameter α_2. In this case it is even more difficult to obtain any bound from neutrino experiments since for neutrino masses m_i only upper bounds exist.

If we consider according to ref. [9] the upper bound of $\alpha_{ext} \sim \sqrt{10^{-3}}$ as its absolute value, and the dominant contribution to the local gravitational potential to be due to the great attractor, which is about $\phi_N = 3 \cdot 10^{-5}$, we can estimate the bounds on the dilaton couplings. Although this bound cannot be taken seriously, this allows us to compare our result with earlier results. Only in the almost degenerate case $(m_1 \sim m_2 \sim m)$, assuming $m = 2.5$ eV (as an upper bound obtained from tritium beta decay experiments [16]) and only for the case the vacuum oscillation solution of the solar neutrino problem will turn out to be realized in nature, the experimental Δm^{*2} may be large enough to imply a significant bound (see however the discussion of medium effects in [10]). The search for neutrinoless double beta decay [17], implying $M_{+dil} < 0.3$ eV suffers from an even more severe suppression, since the bound for M_+ is less stringent than the one for Δm^{*2}.

In summary, we point out that the dilaton exchange gravity cannot be constrained substantially in the neutrino sector, while the bound coming from the $K_L - K_S$ mass difference is significant, modulo the uncertainty of classical background potential. Unlike the new tensorial or vectorial gravitational interactions, this scalar interaction cannot introduce any CPT violation in the $K-$system.

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