Equivalence Principle Violations and Couplings of a Light Dilaton

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(Einstein) Equivalence "Principle" (EP)

- Not a basic principle of physics

- A heuristic generalization of an experimental fact: "hypothesis of equivalence" (Einstein) $\longrightarrow$ very successful in building General Relativity (GR)

Einstein's GR:

$$\eta_{\mu\nu} \longrightarrow g_{\mu\nu}(x)$$

absolute, rigid spacetime	elastic spacetime, dynamically influenced by matter

BUT all the coupling constants of local (special relativistic) physics remain as absolute and rigid as in Special Relativity (SR):

$$g_a, Y, \lambda_{\rm BEH}, \mu_{\rm BEH} \rightarrow \text{ non dynamical } g_a, Y, \lambda_{\rm BEH}, \mu_{\rm BEH}$$

What determines the coupling constants?

• Very unsatisfactory to put them by hand: this is against the "principle of reason" nihil est sine ratione (Leibniz)

• The history of physics suggests that there are no absolute structures in physics

Kaluza-Klein's idea:

$$g_1 \quad \text{or} \quad \alpha_{\rm em} \simeq \frac{3}{8} \frac{g_1^2}{4\pi\hbar c} \simeq \frac{1}{137} \quad \longrightarrow \quad g_{55}(x)$$

higher-dimensional
elastic spacetime

Dynamical symmetry breaking: the vacuum state minimizes the energy $V(\phi)$ which dynamically determines

$$\langle\phi\rangle \sim \frac{\mu}{\sqrt{\lambda}} \longrightarrow m_e \sim Y_e \langle\phi\rangle \sim Y_e \frac{\mu}{\sqrt{\lambda}}$$

Varying Coupling Constants and EP Violations

Then if any of the coupling constants of local physics (e.g., $\alpha_{\rm em}$, m_e/m_p, m_q/m_p, $\ldots$) is x-dependent

$\Longrightarrow$ violation of equivalence principle (Dicke 1962)

Notably violation of universality of free fall

$$S_{\rm mi} = -\int m_i[\alpha(x), \ldots] \sqrt{-g_{\mu\nu}(x)\, dx^\mu\, dx^\nu}$$

Composition-dependent acceleration

$$\vec{a}_i = \vec{g} - \vec{\nabla}\, \ell n\, m_i[\alpha(x), \ldots] = \vec{g} - \frac{\partial\, \ell n\, m_i}{\partial\, \alpha}\, \vec{\nabla}\, \alpha - \ldots$$

General dilaton-like model of EP violations

Assume general dependence of coupling "constants" on some "dilaton" field φ : $\alpha_{EM}(\varphi), (m_q/\Lambda_{QCD})(\varphi), (m_e/\Lambda_{QCD})(\varphi), \ldots$. Then the dependence of m_A upon fundamental coupling constants:

$$m_A = \Lambda_{QCD}\, \hat{m}_A \left(\alpha_{EM}, \frac{m_u}{\Lambda_{QCD}}, \frac{m_d}{\Lambda_{QCD}}, \frac{m_e}{\Lambda_{QCD}}\right)$$

$\rightarrow$ a φ dependence of m_A and a corresponding dilaton coupling to m_A

$$\alpha_A = \frac{\partial \ln m_A(\varphi)}{\partial \varphi}$$

Composition-dependent modification of Newtonian interaction

$$V(r) = -G\,\frac{m_A\, m_B}{r}\,(1 + \alpha_A\, \alpha_B\, e^{-m_\varphi r})$$

In the following: inverse range of φ : $m_\varphi = 0$. $\rightarrow$ Weak EP violation

$$\eta_{AB} = \left(\frac{\Delta a}{a}\right)_{AB} \simeq (\alpha_A - \alpha_B)\,\alpha_E$$

General Dilaton Low-energy Couplings (Damour-Donoghue10)

Organizing principle: keep track of all the possible φ couplings entering the effective action describing physics at the scale of nucleons. At this scale: heavy quarks (c, b, t; and, arguably, s) are integrated out.

$$\mathcal{L}_{\rm eff} = -\frac{1}{4e^2} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4} F^A_{\mu\nu} F^{A\mu\nu} + \sum_{i=e,u,d} \left[i\bar{\psi}_i \not{D}(A, g_3 A^A) \psi_i - m_i \bar{\psi}_i \psi_i \right]$$

Five terms in $\mathcal{L}_{\rm eff}$ $\rightarrow$ five possible (dimensionless) φ couplings: $d_e, d_g, d_{m_e}, d_{m_u}, d_{m_d}$

$$\mathcal{L}_{\rm int\varphi} = \varphi \left[+ \frac{d_e}{4e^2} F_{\mu\nu} F^{\mu\nu} - \frac{d_g \beta_3}{2 g_3} F^A_{\mu\nu} F^{A\mu\nu} - \sum_{i=e,u,d} (d_{m_i} + \gamma_{m_i} d_g) m_i \bar{\psi}_i \psi_i \right] .$$

Relation between dilaton couplings d_a and the "constants of Nature"

The five possible dilaton couplings $d_a = \{d_e, d_g, d_{m_e}, d_{m_u}, d_{m_d}\}$ are equivalent to:

fine-structure constant $\alpha = \frac{e^2}{4\pi} \simeq \frac{1}{137} \to \alpha(\varphi) = (1 + d_e\,\varphi)\,\alpha$

QCD energy scale $\Lambda_3 \sim 100\,\mathrm{MeV} \to \Lambda_3(\varphi) = (1 + d_g\,\varphi)\,\Lambda_3$

electron mass $m_e \to m_e(\varphi) = (1 + d_{m_e}\,\varphi)\,m_e$

light-quark masses at QCD scale $m_i(\Lambda_3) \to [m_i(\Lambda_3)](\varphi) = (1 + d_{m_i}\,\varphi)\,m_i(\Lambda_3)$, $i = u, d$

Ratios of dimensional parameters

As the Planck scale $1/\kappa = 1/\sqrt{4\pi G}$ does not directly enter physics at the QCD scale (besides its possible impact on Λ_3 via $\Lambda_{\text{cut-off}} \propto 1/\kappa$?) :

Mass of an atom:

$$m_A = \Lambda_3 \, M_A \left(\frac{m_u}{\Lambda_3}, \frac{m_d}{\Lambda_3}, \frac{m_e}{\Lambda_3}, \alpha \right)$$

where M_A is a dimensionless function of four dimensionless quantities:

$$k_a = (k_u, k_d, k_e, k_\alpha) \equiv \left(\frac{m_u}{\Lambda_3}, \frac{m_d}{\Lambda_3}, \frac{m_e}{\Lambda_3}, \alpha \right)$$

Composition-dependence of φ coupling to atom

$$\alpha_A = \frac{\partial \ln[\kappa m_A(\varphi)]}{\partial \varphi} = \sum_a \frac{\partial \ln[\kappa m_A(k_a)]}{\partial k_a} \frac{\partial k_a}{\partial \varphi}$$

$$\alpha_a = d_g + \bar{\alpha}_A$$

where $d_g = \frac{\partial \ln \Lambda_3}{\partial \varphi}$ is a universal (non EP-violating) contribution and

$$\bar{\alpha}_A = \frac{1}{M_A} \frac{\partial M_A}{\partial \varphi} = \frac{1}{M_A} \left[\sum_{a=u,d,e} (d_{m_a} - d_g) \frac{\partial M_A}{\partial \ln k_a} + d_e \frac{\partial M_A}{\partial \ln \alpha} \right].$$

Analysis of scalar couplings to the binding energy of nuclei

Need to relate the various contributions to the nuclear binding energy

$$E^{\rm bind} = -a_v A + a_s A^{2/3} + a_a \frac{(A-2Z)^2}{A} + a_c \frac{Z(Z-1)}{A^{1/3}} - \delta \frac{a_p}{A^{1/2}}$$

to the variability of light quark masses m_u, m_d, or $\hat{m} = \frac{m_d + m_u}{2}$, $\delta m = m_d - m_u$.

Possible by combining Walecka-type analysis of nuclei binding (parametrized by scalar and vector coupling strengths G_S, G_V) with recent work of Donoghue (2006) on the pion-mass dependence of G_S and G_V:

$$\bar{\alpha}_A^{\rm bind} = -\frac{(d_{\hat{m}} - d_g)}{m_A}(120A - 97A^{2/3}) m_\pi^2 \frac{\partial \eta_S}{\partial m_\pi^2}$$

$$\hat{m} \frac{\partial \eta_S}{\partial \hat{m}} = m_\pi^2 \frac{\partial \eta_S}{\partial m_\pi^2} = -0.35 \pm 0.10$$

Implications for the Equivalence Principle

$$\alpha_A = d_g + \bar{\alpha}_A$$

$$\bar{\alpha}_A = \left[(d_{\hat{m}} - d_g) Q_{\hat{m}} + (d_{\delta m} - d_g) Q_{\delta m} + (d_{m_e} - d_g) Q_{m_e} + d_e Q_e\right]_A$$

where the various “dilaton charges” Q_{k_a} are given by
(with $F_A \equiv A\, m_{amu}/m_A \simeq 1$)

$$Q_{\hat{m}} = F_A \left[0.093 - \frac{0.036}{A^{1/3}} - 0.020 \frac{(A-2Z)^2}{A^2} - 1.4 \times 10^{-4}\, \frac{Z(Z-1)}{A^{4/3}}\right],$$

$$Q_{\delta m} = F_A \left[0.0017\, \frac{A-2Z}{A}\right],$$

$$Q_{m_e} = F_A \left[5.5 \times 10^{-4}\, \frac{Z}{A}\right],$$

$$Q_e = F_A \left[-1.4 + 8.2 \frac{Z}{A} + 7.7 \frac{Z(Z-1)}{A^{4/3}}\right] \times 10^{-4}.$$

Simplified Parametrization of EP Violations

Under plausible approximations, only two dilaton charges dominate:

$Q'_{\hat{m}}$ linked to average quark-mass sensitivity to nuclear binding, and $Q'_{\alpha} \equiv Q'_{e}$ linked to the fine-structure constant:

$$\alpha_A \simeq d_g^* + \left[(d_{\hat{m}} - d_g)Q'_{\hat{m}} + d_e Q'_e\right]_A$$

$$Q'_{\hat{m}} = -\frac{0.036}{A^{1/3}} - 1.4 \times 10^{-4}\,\frac{Z(Z-1)}{A^{4/3}}$$

$$Q'_e = +7.7 \times 10^{-4}\,\frac{Z(Z-1)}{A^{4/3}}.$$

Approximate EP-violating "dilaton charges"

Table : Approximate EP-violating 'dilaton charges' for a sample of materials. These charges are averaged over the (isotopic or chemical, for SiO_2) composition.

Material	A	Z	$-Q'_{\hat{m}}$	Q'_e
Li	7	3	18.88×10^{-3}	0.345×10^{-3}
Be	9	4	17.40×10^{-3}	0.494×10^{-3}
Al	27	13	12.27×10^{-3}	1.48×10^{-3}
Si	28.1	14	12.1×10^{-3}	1.64×10^{-3}
SiO_2	...	...	13.39×10^{-3}	1.34×10^{-3}
Ti	47.9	22	10.28×10^{-3}	2.04×10^{-3}
Fe	56	26	9.83×10^{-3}	2.34×10^{-3}
Cu	63.6	29	9.47×10^{-3}	2.46×10^{-3}
Cs	133	55	7.67×10^{-3}	3.37×10^{-3}
Pt	195.1	78	6.95×10^{-3}	4.09×10^{-3}

Composition-dependence of weak EP violations

General possible (dilaton-like) phenomenology (Damour-Polyakov'94, Dent'08, Damour-Donoghue'10): $A \equiv N + Z$

$$\left(\frac{\Delta a}{a}\right)_{AB} = \left[\frac{c_1}{A^{1/3}} + c_2 \frac{Z^2}{A^{4/3}} + c_3 \frac{A-2Z}{A} + c_4 \frac{(A-2Z)^2}{A^2}\right]_{AB}$$

Plausible simplified (dilaton-like) phenomenology (Damour-Donoghue2010)

$$\left(\frac{\Delta a}{a}\right)_{AB} \simeq \left[\frac{c_1}{A^{1/3}} + c_2 \frac{Z^2}{A^{4/3}}\right]_{AB}$$

Two dominant EP signals, linked to nuclear physics (variation of $m_q/\Lambda_{\rm QCD}$) and Coulomb effects (variation of $\alpha_{\rm EM} = e^2/\hbar c$)

Two material pairs suffice to constrain the two dominant EP parameters c_1, c_2

Dilaton-like models allow to a priori compare the sensitivity of various EP tests: e.g. the "dilaton charge vector" of the pair Rb^{85}, Rb^{87} can be compared to that of Pt, Ti and is found to be $\sim 10^{-2}$ smaller.

Present Experimental Bounds

Using the two current EP experiments that have reached the 10^{-13} level, namely EötWash (Schlamminger et al. 2008)

$$\left(\frac{\Delta a}{a}\right)_{\mathrm{Be\,Ti}} = (\alpha_{\mathrm{Be}} - \alpha_{\mathrm{Ti}})\alpha_{\mathrm{Earth}} = (0.3 \pm 1.8) \times 10^{-13}$$

and Lunar Laser Ranging (Williams et al. 2004, 2009)

$$\left(\frac{\Delta a}{a}\right)_{\mathrm{Earth\,Moon}} = (\alpha_{\mathrm{Earth}} - \alpha_{\mathrm{Moon}})\alpha_{\mathrm{Sun}} = (-1.0 \pm 1.4) \times 10^{-13}$$

one can get constraints on the two dilaton parameters

$$D_{\hat{m}} = d_g^* \,(d_{\hat{m}} - d_g)\,, \qquad D_e = d_g^*\, d_e\,.$$

Namely, at the 2σ level

$$D_{\hat{m}} = \pm 0.87 \times 10^{-9}, \quad D_e = \pm 4.0 \times 10^{-9}\,.$$

Comparing the Experimental Sensitivities of EP Experiments

The simplified dilaton framework contains three independent parameters, d_g (composition-independent) and $d_q \equiv d_{\hat{m}} - d_g$, d_e (composition-dependent). It is quite predictive and can be used as a guideline for comparing and/or planning EP experiments. Examples:

Comparing composition-independent (Eddington's γ-parameter) and composition-dependent

$$1 - \gamma \simeq 2 d_g^2$$

- In dilaton models: $\exists$ also link EP and tests of (PN) gravity

$$\frac{\Delta a}{a} \sim 10^{-2} \, \frac{d_q}{d_g} \, \frac{1 - \gamma^{\mathrm{PPN}}}{2}$$

where $d_q \equiv \partial \, \ell n(m_q/\Lambda_{\mathrm{QCD}})/\partial \varphi$, $d_g \equiv \partial \, \ell n(\Lambda_{\mathrm{QCD}}/m_{\mathrm{Planck}})/\partial \varphi$ and either $d_q \sim d_g$ or $d_q \sim d_g/40$. In the "worst case" $1 - \gamma^{\mathrm{PPN}} \sim 10^4 \, \Delta a/a$ so that $\Delta a/a \sim 10^{-15} \to 1 - \gamma^{\mathrm{PPN}} \sim 10^{-11}$.

Comparing the vectors of dilaton-charge differences

$$(Q'_{\hat{m}}, Q'_e)_{\rm Pt\,Ti} = (3.33, 2.04) \times 10^{-3}$$

vs $\quad (Q_{\hat{m}}, Q_{\delta_m}, Q_{m_e}\, Q_e)_{^{87}Rb\,^{85}Rb} = (-3.3, 3.4, -0.55, -9.2) \times 10^{-5}\,.$

$\exists$ also link between WEP and clock tests of EEP (e.g. grav. redshift) (see, e.g., TD gr-qc/9904032). When comparing frequencies of atomic transitions $A^* \to A$ at two different locations r_1, r_2:

$$\frac{\nu_A^{A^*}(r_1)}{\nu_A^{A^*}(r_2)} \simeq 1 + (1 + \alpha_A^{A^*}\, \alpha_E)(U_E(r_1) - U_E(r_2))$$

where

$$\alpha_A^{A^*} = \frac{\partial \ln E_A^{A^*}}{\partial \varphi}$$

computable from coupling-constant dependence of $E_A^{A^*}$. E.g. for hyperfine transition $E_A^{A^*} \propto m_e\, e^4\, g_I \frac{m_e}{m_p}\, e^4\, F_{\rm rel}(Ze^2)$.

Anthropic-type argument for EP violation (Damour-Donoghue2010)

Independently of any specific theoretical model one might argue (along the "anthropic" approach to the vast "multiverse" of cosmological and/or string backgrounds) that:

- **(i)** the EP is not a fundamental symmetry principle of Nature
- **(ii)** the level $\eta \sim \Delta a/a$ of EP violation can be expected to vary, quasi-randomly, within some range of order unity over the full multiverse
- **(iii)** as there is probably a maximal level of EP-violation, say $\eta_* \neq 0$, which is compatible with the development of life (and physicists), one should a priori expect to observe, in our local environment, an EP violation η of order η_*.

Conclusions (I)

• EP is intimately connected with some of the basic aspects of modern physics, and of the unification of gravity with particle physics.

• The historical tendency of physics to discard any absolute structures, as well as the generalized Kaluza-Klein aspects (moduli) of string theory a priori suggests there could exist EP violations.

• The recent observation of $\rho_{\rm vac} \sim 10^{-123}\, m_{\rm Planck}^4$ poses a challenge to physics which suggests that we are missing some key understanding of IR gravity. This might provide additional motivation for EP violation (either via some Nambu-Goldstone mode, or via anthropic arguments).

• Even within the "majority view" of the "moduli stabilization" issue, EP experiments are testing a key assumption of current string models.

Conclusions (II)

• $\exists$ no firm prediction for level of EP violation, but some phenomenological models show that the violation could naturally be just below the currently tested level.

• In dilaton-like models, the composition-dependence of EP signals is (probably) dominated by two signals, depending on $A^{-1/3}$ and $Z^2 A^{-4/3}$.

• In such dilaton-like models, there exist correlated modifications of gravity ($\Delta a/a$, $\gamma^{\rm PPN} - 1 \neq 0$, $\dot{\alpha}_a \neq 0$, $d\alpha_a/dU \neq 0, \ldots$) but EP tests stand out as our deepest probe of new physics, when compared to, e.g., solar-system ($\gamma^{\rm PPN}$) or clock tests ($\dot{\alpha}_a$ or $d\alpha_a/dU$). Indeed,

$$\frac{\Delta a}{a} \sim 10^{-2} \frac{d_q}{d_g} \frac{1 - \gamma^{\rm PPN}}{2}$$

where $d_q \equiv \partial\, \ell n(m_q/\Lambda_{\rm QCD})/\partial \varphi$, $d_g \equiv \partial\, \ell n(\Lambda_{\rm QCD}/m_{\rm Planck})/\partial\varphi$ and either $d_q \sim d_g$ or $d_q \sim d_g/40$. In the "worst case" $1 - \gamma^{\rm PPN} \sim 10^4\, \Delta a/a$ so that $\Delta a/a \sim 10^{-15} \rightarrow 1 - \gamma^{\rm PPN} \sim 10^{-11}$.