Theoretical Aspects of the Equivalence Principle

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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)

- GR is based on two basic postulates:

(1) EP: Universal coupling of matter to gravity $(\eta_{\mu\nu} \to g_{\mu\nu}(x))$ plus usual coupling constants of special relativistic physics

(2) Dynamics of the gravitational field $g_{\mu\nu}(x)$

$$S = S_{\text{matter}}[\psi, A, \phi; g_{\mu\nu}; g_a, Y, \lambda, \mu] + \int d^4x \sqrt{g}\, \frac{R(g_{\mu\nu})}{16\pi G}$$

Special Relativistic Physics (SM, MSSM, ...)

$$S_{\mathrm{SM}}[\psi, A, \phi; \eta_{\mu\nu}; g_a, Y, \lambda, \mu]$$

based on two types of absolute structures

Space-time structure: $\eta_{\mu\nu}$

Coupling constants:

gauge couplings	g_1, g_2, g_3
Higgs parameters	μ, λ
Yukawa couplings	Y_{ij}
UV cut-off	Λ_{UV}

about 20 parameters in SM and $\sim$ 100 in MSSM

What determines the coupling constants? (I)

• 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

Einstein's GR:

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

absolute, rigid spacetime	elastic spacetime, dynamically influenced by matter

What determines the coupling constants? (II)

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

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

In both cases "external" dynamical effects determine the structure of local "vacuum"

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

$$\alpha_{\rm em} \sim g_{55}(x) \qquad \text{(if KK)}$$

$$m_i \sim Y_i \, \frac{\mu}{\sqrt{\lambda}}$$

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

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

Composition-dependence of EP violations

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

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

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

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

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

String-inspired motivation for EP violation

String theory:

• “magically” unites Relativistic Quantum Theory with GR

$$\{\eta_{\mu\nu} + \text{string} + \hbar\} \longrightarrow \text{dynamical } g_{\mu\nu}(x)$$

• naturally unifies gauge-theories (A_μ) with gravity $(g_{\mu\nu})$, and more generally matter, interactions and space-time

• at face value, string theory contains no arbitrary coupling constants, and is a vast generalization of the Kaluza-Klein idea

$$g_a^{D=4} = f(\langle\phi_1(x)\rangle, \langle\phi_2(x)\rangle, \ldots, \langle\phi_n(x)\rangle, \ldots)$$

many scalar (moduli) fields of dynamical origin: compactified dimensions, brane positions,...

The dynamical nature of all coupling constants (and mass ratios) in string theory a priori suggests the presence of EP violations.

However, it seems (in the weak coupling domain) that if the moduli fields stay massless, the level of EP violation would be phenomenologically too large (and would also jeopardize inflation)

Majority view: try to find "string vacua" which stabilize all moduli fields at the minimum of some effective potential $V(\phi_1, \phi_2, \ldots)$

$\Longrightarrow$ all moduli acquire a mass $m_a^2 \sim \partial^2 V / \partial \phi_a^2$ (see Denef2008)

EP tests are important because they test an assumption commonly made in string theory, and could refute it.

String-inspired cosmological attractor mechanism

A different scenario for trying to reconcile the existence of (massless) moduli with phenomenology (Damour-Polyakov, Damour-Piazza-Veneziano).

Modulo some assumption about the (strong-field) behaviour of the coupling functions $g_a(\phi)$ of moduli, ϕ might be cosmologically attracted towards a value ϕ_* where ϕ_* decouples from matter.

This mechanism naturally generates $\Delta a/a \ll 1$ without using small parameters.

It gives an "existence proof" of an EP violation which is naturally below the currently tested level $\Delta a/a \sim 10^{-13}$

Motivation from the observed dark energy

The observation of dark energy $\rho_{\rm vac} \sim 10^{-123}\, m_{\rm Planck}^4 \neq 0$ poses a challenge.

May be it is an indication of a $V(\phi)$ relaxing towards zero ("quintessence", Wetterich, ..., Steinhardt, ...), which suggests the existence of EP violations linked to the nearly massless ϕ.

May be the solution of the challenge involves some type of spontaneous breaking of scale invariance (Wetterich, ..., Rabinovici2008). Then, under some assumptions (Wetterich08) such a scenario might realize the runaway version of the cosmological attractor scenario, with associated small EP violation.

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 $\Delta a/a \sim 10^{-15} \to 1 - \gamma^{\rm PPN} \sim 10^{-11}$.