Violation of the weak equivalence principle due to gravity-matter entanglement

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Abstract

We show the violation of the Weak Equivalence Principle in the presence of the entanglement between gravity and matter [1]. We analyse a simple toy scenario in which the entangled gravity-matter state consists of two terms: a dominant (classical) one, and a small perturbation. We rewrite the new geodesic equation as a geodesic equation for the dominant classical metric plus a contribution, coming from the interference terms between the dominant and perturbative gravity-matter fields. The additional term represents the deviation from the original geodesic equation due to the presence of gravity-matter entanglement, and measures the violation of the weak equivalence principle.

Weak Equivalence Principle (WEP)

The local effects of particle motion in a gravitational field are indistinguishable from those of an accelerated observer in flat spacetime.

Consequence

A particle in a gravitational field should follow the geodesic, since this is how the straight line in flat space looks like from the accelerated frame.

Single-pole approximation

$$T^{\mu\nu}(x) = \int_{\mathcal{C}} d\tau\, B^{\mu\nu}(\tau) \frac{\delta^{(4)}(x - z(\tau))}{\sqrt{-g}} \qquad (1)$$

Conservation of stress-energy tensor

We assume the local Poincaré invariance for *both* $S_G[g]$ and $S_M[g,\phi]$

$$\nabla_\nu T^{\mu\nu} = 0 \qquad (2)$$

Derivation of WEP (geodesic motion) from General Relativity

Replacing (2) into (1), we obtain the geodesic equation, with $u^\mu \equiv \frac{dz^\mu(\tau)}{d\tau}$ and $u^\mu u_\mu \equiv -1$

(Mathisson and Papapetrou [2, 3]; see also [4])

$$u^\lambda \nabla_\lambda u^\mu = 0$$

Quantising gravity

Fundamental gravitational degrees of freedom $\hat{g}$ and $\hat{\pi}_g$:

$$\Delta\hat{g}\Delta\hat{\pi}_g \geq \frac{\hbar}{2} \qquad \Delta\hat{\phi}\Delta\hat{\pi}_\phi \geq \frac{\hbar}{2}$$

$$|\Psi\rangle = |g\rangle \otimes |\phi\rangle$$

$|g\rangle$ and $|\phi\rangle$ – coherent states of gravity and matter.

$$g_{\mu\nu} \equiv \langle\Psi|\hat{g}_{\mu\nu}|\Psi\rangle \qquad T_{\mu\nu} \equiv \langle\Psi|\hat{T}_{\mu\nu}|\Psi\rangle$$

Violation of WEP due to entanglement

$$|\boldsymbol{\Psi}\rangle = \alpha|\Psi\rangle + \beta|\tilde{\Psi}\rangle$$

Perturbation, with coherent classical states $|\tilde{g}\rangle$ and $|\tilde{\phi}\rangle$

$$|\tilde{\Psi}\rangle = |\tilde{g}\rangle \otimes |\tilde{\phi}\rangle$$

"Entangled" metric $\boldsymbol{g}_{\mu\nu} = \langle\boldsymbol{\Psi}|\hat{g}_{\mu\nu}|\boldsymbol{\Psi}\rangle$

$$\boldsymbol{g}_{\mu\nu} = g_{\mu\nu} + \beta\, h_{\mu\nu} + \mathcal{O}(\beta^2)$$

$$h_{\mu\nu} = 2\,\mathrm{Re}\Big[\langle\Psi|\hat{g}_{\mu\nu}|\tilde{\Psi}\rangle - \langle\Psi|\tilde{\Psi}\rangle g_{\mu\nu}\Big]$$

$$u^\lambda \nabla_\lambda u^\mu + \beta\left(\nabla_\rho h^\mu{}_\nu - \frac{1}{2}\nabla^\mu h_{\nu\rho}\right) u^\rho u^\nu + \mathcal{O}(\beta^2) = 0$$

Manifestly covariant correction of the "entangled" geodesic equation

$$\frac{d^2 z^\mu(\tau)}{d\tau^2} + \boldsymbol{\Gamma}^\mu{}_{\rho\nu}\frac{dz^\rho(\tau)}{d\tau}\frac{dz^\nu(\tau)}{d\tau} = 0\,,$$

where the Cristoffel symbols are given by:

$$\boldsymbol{\Gamma}^\mu{}_{\rho\nu} = \frac{1}{2}\boldsymbol{g}^{\mu\sigma}(\partial_\rho \boldsymbol{g}_{\nu\sigma} + \partial_\nu \boldsymbol{g}_{\sigma\rho} - \partial_\sigma \boldsymbol{g}_{\rho\nu})\,.$$

Discussion

- Both matter and gravity are considered quantum — no semiclassical approximations and the associated errors.
- In Newtonian physics, due to the specific dynamical and gravitational laws ($m_i a = m_g g$), WEP implies the equality of two types of masses, $m_i = m_g$. The laws of quantum mechanics, however, may not directly imply that $m_i = m_g$ as a consequence of WEP. On the other hand, the deviation from the geodesic trajectory is a more universal signal of WEP violation.
- Further analysis of (2) for the 'entangled" stress-energy tensor $\boldsymbol{T}_{\mu\nu} = \langle\boldsymbol{\Psi}|\hat{T}_{\mu\nu}|\boldsymbol{\Psi}\rangle$ can be done — obtaining the domain of validity of the single-pole approximation.
- Quantitative analysis might allow for possible future experimental verification of the gravity-matter entanglement and thus an answer to the open question of the necessity of quantising gravity.

References

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