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

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Weak Equivalence Principle

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.

Deriving WEP (geodesic motion) in GR

Single-pole approximation:

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

Conservation of stress-energy tensor (assuming the local Poincaré invariance for *both* $S_G[g]$ and $S_M[g, \phi]$):

$$\nabla_\nu T^{\mu\nu} = 0 \, . \tag{2}$$

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]):

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

Using Cristoffel symbols,

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

Quantising gravity

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

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

Separable state ($|g\rangle$ and $|\phi\rangle$ – coherent states of gravity and matter):

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

Effective classical metric and stress-energy tensors:

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

Violation of WEP due to entanglement

Entangled state (perturbation $|\tilde{\Psi}\rangle = |\tilde{g}\rangle \otimes |\tilde{\phi}\rangle$, with coherent classical states $|\tilde{g}\rangle$ and $|\tilde{\phi}\rangle$):

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

"Entangled" metric:

$$\boldsymbol{g}_{\mu\nu} = \langle\boldsymbol{\Psi}|\hat{g}_{\mu\nu}|\boldsymbol{\Psi}\rangle = g_{\mu\nu} + \beta\,h_{\mu\nu} + \mathcal{O}(\beta^2)\,.$$

The perturbation is evaluated to be:

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

"Entangled" geodesic equation with the manifestly covariant correction:

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

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

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THANK YOU!