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Short communication

Emergence of Gravitational Coupling from Quantum Action and Vacuum Geometry

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Abstract

We propose a quantum-geometric framework in which gravitational coupling emerges from the requirement that spacetime maintains a quantum-scale action of order ħ. Starting from the zero-point energy of quantum oscillations and a minimal spacetime volume element, we construct an action-based balance between vacuum energy and geometric curvature. This leads to a natural derivation of a coupling relation of the form $\kappa \sim \frac{4\pi\ell^2\omega}{E_0 c}$. Unlike conventional approaches, the derivation avoids direct use of the gravitational constant *G*, thereby addressing circularity issues in Planck-scale arguments. We interpret gravity as an emergent geometric response required to preserve quantum coherence of action in spacetime.

Introduction

The relationship between quantum mechanics and gravitation remains an open problem in theoretical physics [1-9]. Traditional approaches often rely on Planck-scale definitions that explicitly contain the gravitational constant *G*, leading to circular reasoning when attempting to derive gravitational coupling.

In this work, we explore an alternative approach based on the principle that the action associated with a fundamental spacetime region is of order ħ [7]. This assumption is consistent with the role of ħ as the characteristic scale of quantum processes.

Quantum-Geometric Action Framework and Derivation of *k*

We develop a local, action-based framework to relate quantum vacuum fluctuations with spacetime geometry, avoiding any prior assumption of the gravitational constant *G*.

Quantum action scale

We model the vacuum as a collection of harmonic modes with ground-state energy [7]:

$$E_0 = \frac{1}{2}\hbar\omega \tag{1}$$

The characteristic coherence timescale is:

$$\Delta t \sim \frac{1}{\omega} \tag{2}$$

Thus, the action associated with a fundamental vacuum mode is:

$$S_q \sim E_0 \Delta t \sim \hbar \tag{3}$$

This establishes ħ as the natural scale of quantum action.

Effective geometric action of a vacuum cell

We consider a localized spacetime region ("vacuum cell") characterized by a length scale *l*. The corresponding spacetime

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volume is estimated as:

$$d^4x \sim \ell^3 \Delta t \sim \frac{\ell^3}{\omega} \tag{4}$$

This choice reflects a coherent spacetime cell whose temporal extent is set by the inverse frequency of the vacuum oscillation.

We define an effective geometric action for this cell in analogy with the Einstein-Hilbert form:

$$S_g \sim \frac{1}{\kappa}\int R d^4x \tag{5}$$

We assume a characteristic local curvature scale associated with the vacuum fluctuation:

$$R \sim \frac{1}{\ell^2} \tag{6}$$

This represents a localized geometric response rather than global spacetime curvature.

Substituting, we obtain:

$$S_g \sim \frac{1}{\kappa} \cdot \frac{1}{\ell^2} \cdot \frac{\ell^3}{\omega} = \frac{\ell}{\kappa\omega} \tag{7}$$

Consistency condition and emergence of coupling

We impose a consistency condition that the geometric response of spacetime is of the same order as the quantum action scale:

$$S_g \sim S_q \tag{8}$$

Thus:

$$\frac{\ell}{\kappa\omega} \sim \hbar \tag{9}$$

Solving for k:

$$\kappa \sim \frac{\ell}{\hbar\omega} \tag{10}$$

Using the ground-state relation $E_0 = \frac{1}{2}\hbar\omega$, we rewrite:

$$\kappa \sim \frac{\ell}{E_0} \tag{11}$$

To incorporate relativistic scaling and isotropic geometry, we introduce the speed of light c and a spherical normalization factor 4π, yielding:

$$\kappa \approx \frac{4\pi\ell^2\omega}{E_0 c} \tag{12}$$

This expression has dimensions consistent with G/c^4, [5,6] i.e., length per unit mass, and represents the emergent coupling between vacuum energy and spacetime geometry.

Interpretation

This result suggests that gravitational coupling emerges from the requirement that spacetime maintains quantum-scale action [8,9]. In this view:

- Gravity is not fundamental, but emergent
- The coupling constant reflects vacuum properties
- Geometry responds to maintain quantum coherence

Discussion

Unlike Planck-scale derivations, this framework does not assume the gravitational constant G a priori. Instead, k arises as a consistency parameter linking quantum energy and spacetime geometry.

The approach suggests that gravitational effects may depend on underlying quantum scales [6,10], potentially leading to scale-dependent behavior at high energies.

Limitations

This derivation is heuristic and relies on order-of-magnitude estimates. In particular:

- The curvature estimate is approximate
- The action balance condition is assumed
- No explicit field equations are derived

Conclusion

We have presented an action-based framework in which gravitational coupling emerges from quantum vacuum considerations. By requiring that spacetime action remains of order ħ, we derive a coupling relation linking energy, frequency, and geometry.

This approach avoids circular dependence on G and offers a new perspective on the origin of gravitational interaction.

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