Peer Review Report

On "Probing a gravitational cat state: Experimental possibilities"

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Edoardo Livolsi – Independent Researcher

Summary

The manuscript discusses possible experimental schemes for preparing and probing a so-called "gravitational cat state", defined as a spatial superposition of a massive object and its associated gravitational field.

The central claim of the paper is that a quantum superposition of a massive source generates a corresponding superposition state of the gravitational field, which could in principle be probed experimentally.

This claim is conceptually incorrect. The paper suffers from fundamental theoretical inconsistencies, category errors, and unjustified analogies. No genuine quantum state of the gravitational field is defined, no observable distinguishing classical from quantum gravity is identified, and no internally consistent measurement theory is provided.

Major Conceptual Errors

1. Force and gravitational field incorrectly treated as operators

In Sections 1.1 and 1.2 the authors argue that, since the position of a mass is a quantum operator, the Newtonian force and the gravitational field must also be operators.

This inference is false.

In standard quantum mechanics coupled to classical gravity, the gravitational potential is a classical functional of the quantum mass density. The force is computed from expectation values,

$$\langle F \rangle = \int dx \, |\psi(x)|^2 F(x),$$

and does not define a quantum operator acting on an independent Hilbert space.

No operator algebra, commutation relations, or field degrees of freedom are introduced. Therefore, no quantum state of the gravitational field exists in the framework used.

2. Misuse of the term "gravitational cat state"

The statement that a superposition of source positions "generates a cat state of the gravitational field" is a misuse of language.

A cat state requires:

- a quantum field with independent degrees of freedom,
- orthogonal or distinguishable field states,
- a well defined Hilbert space structure.

None of these elements are present. The construction amounts to a classical probability distribution over Newtonian fields conditioned on a quantum source.

This is semiclassical gravity, not quantum gravity.

3. Incorrect identification with the Jaynes–Cummings model

In Section 1.3 the Hamiltonian

$$H = \nu\sigma_1 + \omega a^\dagger a + g\sigma_3(a + a^\dagger)$$

is identified as a Jaynes–Cummings Hamiltonian.

This identification is incorrect.

The Jaynes–Cummings model requires the rotating wave approximation and a specific interaction structure. The Hamiltonian written corresponds, at best, to a spin–boson model in the ultra-strong coupling regime.

Importing intuition about Rabi oscillations and measurement regimes from the Jaynes–Cummings model is therefore unjustified.

4. Ad hoc and physically meaningless probing condition

The probing condition given in Eq. (11) is introduced without derivation, physical interpretation, or connection to a measurement theory.

It serves only to demonstrate that all conceivable experimental realizations are many orders of magnitude out of reach, which the authors themselves repeatedly acknowledge.

As a result, the proposed probing schemes have no physical relevance.

Lack of Experimental Discriminability

Throughout Sections 3 and 4 the analysis consists of order-of-magnitude estimates comparing gravitational forces with projected sensitivities.

However, no observable is identified that would distinguish:

- a quantum superposition of a mass coupled to a classical gravitational field,
- from a genuinely quantized gravitational field.

All quantities considered reduce to expectation values or classical correlation functions of forces. No experiment discussed could falsify semiclassical gravity.

Internal Inconsistency

In Section 4.3 it is suggested that interaction with a classical probe causes the gravitational field to undergo "quantum jumps".

This is internally inconsistent. A classical gravitational field cannot undergo quantum jumps. If gravity is assumed classical, no collapse of the gravitational field is defined. If gravity is quantum, it must be quantized from the outset.

The paper alternates between these two positions without resolving the contradiction.

Conclusion

The manuscript does not present a coherent theoretical framework for gravitational cat states, nor does it identify experimentally testable consequences of gravitational field quantization.

The work consists of a semiclassical analysis accompanied by speculative language and unsupported analogies to quantum optical models.

No new physical predictions are provided, and no experimental scheme capable of probing quantum aspects of gravity is identified.

Recommendation: Rejection

References

[1] M. Derakhshani, C. Anastopoulos, B. L. Hu, "Probing a gravitational cat state: Experimental possibilities", arXiv:1603.04430v1 (2016).

[2] C. Anastopoulos and B. L. Hu, Class. Quant. Grav. 32, 165022 (2015).

Appendix A: Resolution from the wave function psi

In this Appendix the gravitational interaction generated by a quantum superposition state is derived explicitly from the wave function psi. It is shown that no quantum state of the gravitational field emerges from this construction.

A.1 Quantum state of the source

Consider a massive particle of mass M described by the normalized wave function

$$\psi(x) = \frac{1}{\sqrt{2}} \left[\psi_+(x) + \psi_-(x) \right],$$

where

$$\psi_\pm(x) = \frac{1}{(2\pi\sigma^2)^{3/4}} \exp\left(-\frac{(x \mp L/2)^2}{4\sigma^2} \right).$$

This state represents a spatial superposition of two localized wave packets separated by a distance L.

A.2 Mass density and gravitational potential

The mass density associated with the quantum state is given by

$$\rho(x) = M|\psi(x)|^2.$$

Explicitly,

$$\rho(x) = \frac{M}{2} \left(|\psi_+(x)|^2 + |\psi_-(x)|^2 \right) + M \, \mathrm{Re} \left[\psi_+^*(x)\psi_-(x) \right].$$

For $L \gg \sigma$ the interference term is exponentially suppressed and can be neglected.

The Newtonian gravitational potential generated by the source satisfies the Poisson equation

$$\nabla^2\Phi(x) = 4\pi G\rho(x).$$

The solution is

$$\Phi(x) = -G\int d^3x'\,\frac{\rho(x')}{|x-x'|}.$$

A.3 Gravitational force on a probe

The gravitational force acting on a probe mass m located at position R is

$$F(R) = -m\nabla\Phi(R).$$

Substituting the expression for $\rho(x)$ yields

$$F(R) = \frac{1}{2}\left[F_+(R) + F_-(R)\right],$$

where $F_\pm(R)$ are the classical Newtonian forces generated by a point mass M localized at $\pm L/2$.

No operator valued force or field appears at any stage of the derivation.

A.4 Absence of gravitational field superposition

The gravitational field depends only on the classical mass density $\rho(x)$ derived from $|\psi(x)|^2$.

The quantum superposition of the source position does not imply a superposition of gravitational field states. The resulting field is a single classical field sourced by the averaged mass density.

All observable quantities reduce to classical expectation values,

$$\langle F\rangle = \int dx\,|\psi(x)|^2F(x).$$

A.5 Consequence

Starting from the wave function psi and applying standard non-relativistic quantum mechanics coupled to Newtonian gravity, the resulting gravitational interaction is uniquely determined and classical.

No gravitational cat state, no field quantization, and no independent Hilbert space for the gravitational field emerge from this procedure.

Any claim of a quantum superposition of the gravitational field based solely on a superposed source wave function is therefore unfounded.

Appendix B: Absence of gravitational field superposition

In this Appendix it is shown that a quantum superposition of a massive source does not imply a quantum superposition of the gravitational field, even at the level of observables and correlation functions.

The result follows directly from standard non relativistic quantum mechanics coupled to Newtonian gravity.

B.1 Gravitational field sourced by a quantum state

In Newtonian gravity the gravitational potential Phi generated by a mass density rho(x) satisfies

$$\nabla^2 \Phi(x) = 4\pi G \rho(x).$$

For a quantum particle of mass M described by a wave function $\psi(x)$, the mass density entering the Poisson equation is

$$\rho(x) = M|\psi(x)|^2.$$

Therefore the gravitational field is a deterministic functional of the probability density and not an independent quantum degree of freedom.

B.2 Force acting on a probe

The gravitational force acting on a probe mass m located at position R is given by

$$F(R) = -m\nabla\Phi(R).$$

For a superposition state

$$\psi(x) = \frac{1}{\sqrt{2}}\left(\psi_+(x) + \psi_-(x)\right),$$

the expectation value of the force is

$$\langle F(R) \rangle = \int d^3x \, |\psi(x)|^2 F(R, x).$$

For well separated wave packets the result reduces to

$$\langle F(R) \rangle = \frac{1}{2} \left[F_+(R) + F_-(R) \right],$$

where F_+ and F_- are the classical Newtonian forces generated by a source localized at plus or minus $L/2$.

B.3 Force correlations

The two time force correlation function is

$$\langle F(t)F(t') \rangle = \int d^3x \, |\psi(x)|^2 F(x, t) F(x, t').$$

This expression describes classical statistical correlations induced by the quantum uncertainty of the source position.

No operator valued gravitational field appears and no non commuting observables are involved.

B.4 Absence of field coherence

A genuine quantum superposition of a field requires coherence between distinct field configurations belonging to a Hilbert space.

In the present framework the gravitational field has a single classical configuration determined uniquely by the mass density $\rho(x)$.

Any apparent randomness arises from conditioning on measurement outcomes, not from superposed gravitational field states.

B.5 Final statement

All observable gravitational effects generated by a quantum superposed mass reduce to expectation values and classical correlation functions.

Therefore no gravitational field superposition exists within standard quantum mechanics coupled to Newtonian gravity.

Any claim that a superposition of the source implies a superposition of the gravitational field is mathematically and conceptually unfounded.