Quantum Superposition of Massive Objects and the Quantization of Gravity

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Gravity and Quantum Theory

The lack of a background spacetime structure in general relativity makes it impossible to formulate a quantum theory of gravity by simply applying standard procedures that work for other fields. There have been many suggestions that gravity might be fundamentally classical or that it requires a radical modification of basic tenets of quantum theory. There have at least been equally many arguments that gravity must be quantized.

It is therefore of considerable interest to analyze situations where gravity has a quantum source. Assuming that the source is governed by ordinary quantum theory, is the quantum nature of gravity essential to avoiding inconsistencies? If so, must the "true gravitational degrees of freedom"—as opposed to merely the "Newtonian field of the body"—be quantized?

Gravity and Quantum Theory (cont.)

A Gedankenexperiment proposed several years ago by Mari, De Palma, and Giovannetti can be used to directly address this issue.

Note: In the following, will set $\hbar = c = 1$ and will drop numerical factors of order unity when making estimates.

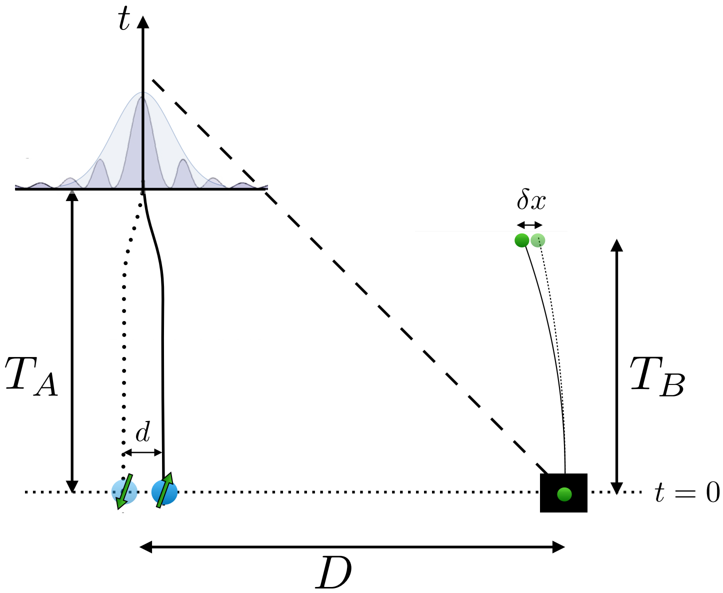
The Gedankenexperiment of Mari et al

- Alice and Bob (separated by distance D) each control a particle, assumed to be nonrelativistic and described by Schrodinger quantum mechanics. In the electromagnetic version, the particles are charged and their gravitational interaction is neglected. In the gravitational version, the particles are uncharged and the gravitational interaction is considered.
- Well prior to time $t = 0$, Alice sent her particle though a Stern-Gerlach apparatus and put it into a 50%-50% superposition, spatially separated by distance $d \ll D$. Prior to $t = 0$, Bob kept his particle in a trap.

The Gedankenexperiment of Mari et al (cont.)

- Beginning at time $t = 0$, Alice sends her particle through a "reversing Stern-Gerlach apparatus" and then performs an interference experiment between the components. She completes this in time T_A.
- Beginning at time $t = 0$, Bob makes the choice of keeping his particle in the trap or releasing it. If he releases it, it's position will become correlated with the components of Alice's particle. Let δx denote the difference in expected position of Bob's particle at time T_B for the different components of Alice's particle.
- If $T_A, T_B < D$ will Alice's interference experiment succeed?

Illustration of the Gedankenexperiment



Analysis of the Electromagnetic Version

State of the system at $t = 0$:

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\Big[|L\rangle_A|\alpha_L\rangle_F + |R\rangle_A|\alpha_R\rangle_F\Big] \otimes |\psi_0\rangle_B$$

We should have $|\langle\alpha_L|\alpha_R\rangle_F| \ll 1$, so in a sense, Alice's particle will have decohered at $t = 0$, before Bob releases his particle and before she attempts to recombine her particle. However, as discussed by Unruh, this is a "false decoherence." If Alice recombines her particle adiabatically and Bob keeps his particle in the trap, Alice will succeed in her interference experiment.

Limitation on Correlation of Bob's Particle

Key limitation on ability of Bob's particle to correlate with Alice's:

Vacuum fluctuations of the quantum electromagnetic field.

Estimate of effect: Over a spacetime region of size R

$$E \sim 1/R^2 \,.$$

Integrating Newton's second law, $m\ddot{x} = qE$, over a time R a classical charged particle will be displaced by

$$\Delta x \sim q/m \,.$$

This should yield a fundamental limit to the quantum localization of a charged body. For significant entanglement of Bob's particle with Alice's, need

$$\delta x > \Delta x = q_B/m_B \,.$$

Limitation on Correlation of Bob's Particle (cont.)

The different components of the wave function of Alice's particle produce an effective dipole $\mathcal{D}_A = q_A d$ and thus an electric field $\sim \mathcal{D}_A / D^3$ near Bob's particle. By Newton's second law, over a time T_B the correlated displacement of Bob's particle will be

$$\delta x \sim \frac{q_B}{m_B} \frac{\mathcal{D}_A}{D^3} T_B^2 \,.$$

Limitation on Coherence of Alice's Particle

Key limitation on coherence of Alice's particle: Emission of quantum electromagnetic radiation. Estimate of effect: When Alice "closes the superposition" of the components of her particle, the effective dipole $\mathcal{D}_A$ will be reduced to zero in time T_A. The corresponding radiated energy will be

$$\mathcal{E} \sim \left(\frac{\mathcal{D}_A}{T_A^2}\right)^2 T_A \, .$$

This energy will appear in the form of photons of frequency $\sim 1/T_A$, so the number of entangling photons will be

$$N \sim \left(\frac{\mathcal{D}_A}{T_A}\right)^2 \, .$$

If $N \gtrsim 1$, the components of Alice's particle will be entangled with emitted photons, and her interference experiment will fail, independently of what Bob does.

Outcome of the Gedankenexperiment

Suppose that $T_A, T_B < D$. In the case (i) $\mathcal{D}_A < T_A$, then $N < 1$, so there will not be enough entangling radiation to destroy the coherence of the components of Alice's particle. On the other hand, the displacement of Bob's particle will be

$$\delta x \sim \frac{q_B}{m_B}\frac{\mathcal{D}_A}{D^3}T_B^2 < \frac{q_B}{m_B}\frac{T_A T_B^2}{D^3} < \frac{q_B}{m_B}$$

so Bob will not be able to acquire "which path" information even if he releases his particle from the trap. In case (i), the Alice's interference experiment will succeed.

On the other hand, in case (ii) $\mathcal{D}_A > T_A$, then Alice's particle will emit entangling radiation, destroying the coherence of the components of its wavefunction. In case (ii), the Alice's interference experiment will fail, independently of what Bob does.

Lessons from the Electromagnetic Gedankenexperiment

Both vacuum fluctuations of the electromagnetic field and the quantization of electromagnetic radiation are essential for obtaining a consistent analysis.

Without vacuum fluctuations, in the case $\mathcal{D}_A < D$, Bob should be able to obtain "which-path" information in time $T_B < D$, violating causality if he influences Alice's state and violating of complementarity if he doesn't.

Similarly, without quantized radiation, in the case where $\mathcal{D}_A > D$, Alice would be able to recohere her particle in time $T_A < D$ (if not influenced by Bob), but Bob can obtain significant "which-path" information in time $T_B < D$, yielding a violation of causality or complementarity.

The Gravitational Gedankenexperiment

Analyze treating (linearized) gravity as a quantum field.
Vacuum fluctuation imply the fundamental localization limit

$$\Delta x \sim l_P$$

where l_P denotes the Planck length. For significant entanglement of Bob's particle with Alice's, need

$$\delta x > \Delta x \sim l_P \,.$$

The Gravitational Gedankenexperiment (cont.)

One might think that, as in the EM case, the different components of the wave function of Alice's particle should produce an effective mass dipole $m_A d$. However, in linearized gravity, it is impossible for an isolated system to produce a mass dipole. Alice's Stern-Gerlach apparatus (plus whatever it is attached to) will produce an equal and opposite mass dipole. Thus, the dominant effect on Bob's particle will be a mass quadrupole $\mathcal{Q}_A \sim m_A d^2$. The displacement of Bob's particle over time T_B will be

$$\delta x \sim \frac{\mathcal{Q}_A}{D^4} T_B^2 \,.$$

The Gravitational Gedankenexperiment (cont.)

On the other hand, the entangling gravitational radiation emitted by Alice's particle will also be quadrupolar in nature. The total energy is

$$\mathcal{E} \sim \left(\frac{\mathcal{Q}_A}{T_A^3}\right)^2 T_A$$

and the number of entangling gravitons is

$$N \sim \left(\frac{\mathcal{Q}_A}{T_A^2}\right)^2 .$$

Outcome of the Gravitational Gedankenexperiment

The analysis now proceeds in complete parallel with the EM case, with "quadrupole" replacing "dipole." If $T_A, T_B < D$, then when $\mathcal{Q}_A < T_A^2$, radiation will not destroy the coherence of Alice's particle, but Bob will be unable to obtain "which path" information. When $\mathcal{Q}_A > T_A^2$, radiation will destroy the coherence of Alice's particle, independently of anything that Bob does.

Conclusions

The quantum properties of the gravitational field with respect to both vacuum fluctuations and the quantization of radiation are essential for obtaining a consistent description of the system. If Alice's and Bob's particles are well described by nonrelativistic quantum mechanics, then (linearized) gravity must possess these key features of a quantum field. Alternatively, if one wishes to deny that a quantum gravitational field displays vacuum fluctuations and/or that gravitational radiation is quantized, one must be prepared to make drastic modifications to the nonrelativistic quantum mechanics of massive particles.