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Research article

Quantum entanglement by gravity as tests of gravitational collapse models *à la* Diósi and Penrose

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Abstract. I provide a simple argument that the experimental observation of gravitationally induced entanglement rules out the validity of current gravitational collapse models. This is consistent with the recent claim to the contrary in [Trillo and Navascués, *Phys. Rev. D*, 111, (2025)], if one takes into account the physical constraints of actual table-top gravity experiments.

Keywords. Quantum optomechanics, gravitational quantum physics, quantum sensing.

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1. Introduction

Our current version of quantum theory does not place fundamental bounds on the ability to prepare quantum superposition states of isolated degrees of freedom of objects (for our purpose here: the center of mass). Decoherence only occurs once we allow coupling to an environment and ignore some of the environmental degrees of freedom [1]. In principle, any sufficiently well-isolated experiment should be able to prevent that from happening. In practice, of course, this may become arbitrarily difficult as increasing system size unavoidably increases the coupling to the environment. One way to see that is in the many current demonstrations of quantum delocalization of massive objects, which span an impressive 17 orders of magnitude in mass: the larger the mass, the smaller the achievable delocalization; from half-meter scale superpositions for single atoms [2], over hundreds of nanometers for macromolecules [3] to picometer and attometer for solid-state mechanical systems [4–7].

If we add gravity to the game, things become (as of to date) undefined. We do not yet have an experimentally backed theory that tells us what the gravitational field of a massive object in a spatial superposition looks like. Our current theory of gravity is a classical field theory that cannot deal with quantum-delocalized source masses [8]. The standard approach of most physicists is to assume that we can extend gravity theory to a quantum field theory, which works reasonably well if one stays away from Planck-scale energies to avoid UV divergence [9,10]. If we stick with this approach then a table-top gravity experiment with delocalized quantum source masses, of the type originally suggested by Feynman [11], has a well-defined outcome given by the low-energy non-relativistic limit of the quantum field theory: the superposition of a source mass will result in a superposition of space-time metrics, which will lead to entanglement with a distant test mass (for a quantitative treatment see e.g. [12–17]). Naturally, if we trace out the test mass we would see decoherence of the source mass superposition, but the overall coherence in the entangled state is maintained and will not decay.[1]

The less standard approach is to assume new physics beyond orthodox quantum theory, one example being gravitational collapse models *à la* Diósi [18–20] and Penrose [21,22] (inspired by early work of Karolyhazy [23]). In a nutshell, in these models gravity adds an intrinsic decoherence mechanism to a spatial superposition of a single mass that is quantified by the gravitational self-energy between the two branches of the superposition. In other words, one has to treat each branch as an actual source of gravitational energy that interacts with the other branch. The dynamics is governed by the von Neumann–Newton equation and results in a computable decoherence rate at which each single-mass superposition state decays [19,24]. Consequently, these gravitational quantum state reduction models pose a fundamental limit to the validity of the superposition principle.

2. Gravitational quantum sensing

For the following discussion consider two masses $m_i = m$ ($i = 1,2$) centered at $\mathbf{z_i} = (0,0,z_i)$ at a distance $d = |\mathbf{z_1} - \mathbf{z_2}|$ along the z-direction. Each mass is prepared in a superposition of its center of mass degree of freedom along the x-direction with a superposition size $\Delta x_i = |\mathbf{x_i} - \mathbf{x}'_{\mathbf{i}}|$ (Figure 1). This specific scenario, first discussed in [14,15], generates entanglement by gravitational interaction at a rate [25]

$$\Gamma_e = \frac{G}{\hbar} m^2 \Delta x^2 d^{-3}. \tag{1}$$

In the idealized case, the two masses are point-like masses and only their center of mass separation and delocalizations Δx are taken into consideration for analyzing the entangling dynamics (Figure 1(a)). In an actual experiment, however, each mass is realized by an extended physical object (here: a sphere of radius R and mass density $\rho(\mathbf{r})$). This imposes additional constraints on the parameter space. Specifically, since two solid-state objects cannot penetrate each other, the centers of mass of two equivalent, homogeneous spheres have to be separated by a distance greater than twice their radius, i.e. $d > 2R$ (Figure 1(b)). In addition, based on the experience from small-scale gravity experiments [26–28], it seems unlikely that isolating gravity as a coupling mechanism in table-top experiments will be possible without a physical shielding mechanism in the form of a conducting Faraday shield between the two masses (Figure 1(c)). This results in two additional restrictions: first, the surface distance $d_s = d - 2R$ between the spheres will have to be in the regime of some micrometer ($\sim 10^{-6}$ m) to accommodate the Faraday shield; second, any finite dissipation in the conducting Faraday shield will lead to localization of the particle due to which-way information in form of image charges in the shield [29,30]. Even in the absence of external charges, unavoidable internal dipole moments (due e.g. to trapping fields or material defects [31]) will have to be shielded in the same way [30]. This decoherence mechanism restricts the ratio between delocalization and distance to the Faraday shield to[2] $\Delta x \ll d/2$ [30].

[1] Note that even if we would start from a more involved quantum theory of gravity, e.g. string theory or loop quantum gravity, we would expect an effective quantum field theory to emerge as the correct description of low-energy quantum gravity phenomena.

[2] The relevant dynamics occurs from an interaction between the virtual dipole formed by charge and mirror-charge distribution, and a point close to the dipole axis within the plane of the Faraday shield. By geometry, any such paraxial

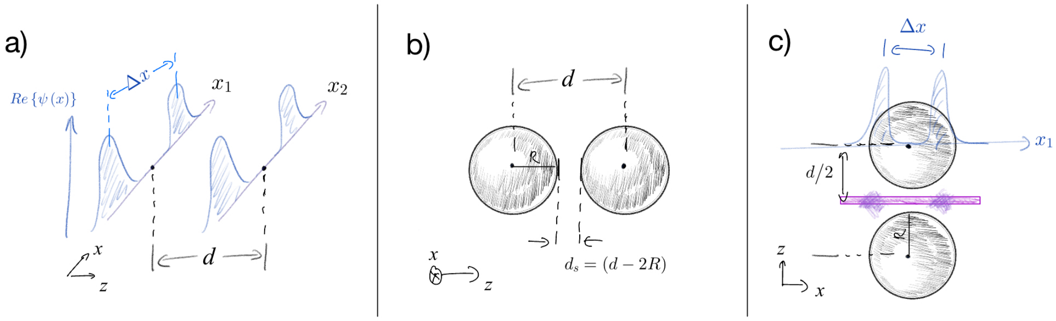

Figure 1. Experimental constraints on entanglement generation by gravity. (a) Idealized experimental scenario assuming two point-like masses with delocalization Δx (along the x-direction) and center-of-mass distance d (along the z-direction). (b) Actual experimental situation with two extended masses of radius R and surface distance d_s, restricting the available parameter space to $d > 2R$. (c) Table-top gravity experiments necessitate electromagnetic shielding in form of a conducting Faraday shield. To avoid decoherence due to image charges requires $\Delta x \ll d/2$.

The immediate and somewhat surprising consequence of these physical constraints is the following: the rate at which entanglement is created (through actual gravitational interaction via Eq. (1)) is always smaller than the intrinsic decoherence rate of each of the masses predicted by gravitational collapse theories. Any observation of entanglement will therefore exclude a decoherence model based on gravitational interaction between branches. In other words: the time required to generate entanglement between delocalized quantum source masses is always larger than the intrinsic "gravity-induced" decoherence time of each delocalized mass, which excludes by principle the generation of entanglement if the idea of gravitational collapse is correct.

To see this quantitatively recall that for gravitational collapse models *à la* Diósi–Penrose the decoherence of a single mass delocalized by Δx in its center of mass degree of freedom is given by [24]

$$\Gamma_d = \frac{E_N(\mathbf{x},\mathbf{x}) - E_N(\mathbf{x}',\mathbf{x}') + 2E_N(\mathbf{x},\mathbf{x}')}{2\hbar}, \tag{2}$$

with the Newtonian gravitational (self-)energy

$$E_N(\mathbf{x},\mathbf{x}') = -G \iint \mathrm{d}\mathbf{r}\,\mathrm{d}\mathbf{r}' \frac{\rho_x(\mathbf{r})\rho_{x'}(\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|}, \tag{3}$$

and with mass density $\rho_x(\mathbf{r})$ for a mass centered at $\mathbf{x}$. Note that the decoherence rate strongly depends on the modeling of the actual mass-density distribution. This has been done in different ways. In early works of Penrose [21] and Diósi [18,19,32], the mass density of the object is assumed to be distributed in form of "little homogenous balls of radius σ" [19]. This is also known as the natural parameter-free version of the Diósi–Penrose model [33]. Since no mass is present outside the physical dimension of the object, the most conservative lower bound on decoherence due to gravitational collapse is given by assuming a homogeneous density distribution over the full extent of the object, i.e. $\sigma = R$. For the case of a spherical mass of radius R this yields

$$\Gamma_d = \begin{cases} \frac{G}{2\hbar} m^2 \Delta x^2 R^{-3}, & \Delta x \ll R, \\ \frac{G}{2\hbar}\frac{6}{5} m^2 R^{-1}, & \Delta x \gg R. \end{cases} \tag{4}$$

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perturbative (Taylor) expansion of the interaction will grow in orders of $\Delta x/d$.

The decoherence rate Γ_d due to gravitational collapse needs to be compared to Γ_e from Eq. (1), i.e. the rate at which entanglement is generated between two gravitationally coupled delocalized quantum source masses. If $\Gamma_d > \Gamma_e$ no entanglement can be generated.[3] The first constraint discussed above is that the gravitating masses are of finite size R and cannot penetrate each other, i.e. $d > 2R$. For the case of small source-mass delocalization $\Delta x \ll R$ this results in $\Gamma_d > 4\Gamma_e$ and hence no entanglement can be generated irrespective of the surface distance d_s between the gravitating spheres. For the case of large source-mass delocalization $\Delta x \gg R$ the decoherence rate saturates and one can expect to find a critical distance d_c below which $\Gamma_e > \Gamma_d$. Concretely, $\Gamma_e/\Gamma_d < (10/12)(\Delta x/d)^2$, which can be made larger than 1 (i.e. entangling) for $(\Delta x/d) \gg 1$.[4] However, the physical constraints of electromagnetic shielding in gravity experiments (see above) restrict the accessible parameter space to $\Delta x \ll 2d$ to prevent decoherence due to localization by image charges in the conducting Faraday shield. As a consequence, $\Gamma_d \gg \Gamma_e$ for all Δx, which means decoherence of the individual masses will happen at a faster rate than the generation of entanglement in any experimental implementation that is predominantly sensitive to gravity.

These results are in agreement with the recent full analysis of the two-mass scenario provided in [34], in which Trillo and Navascués show that the dynamics imposed by gravity models *à la* Diósi–Penrose can be entangling. This is consistent with the view presented earlier that these models introduce an additional but finite decoherence rate (due to gravitational quantum state reduction). They also show that, for a chosen delocalization Δx, entanglement generation is restricted to distances $d < d_c \approx \Delta x + 0.85\sigma$. Here, σ is the regularization parameter that is commonly used in the Diósi–Penrose models to parametrize the effect of mass-density distribution in form of Gaussian-smeared points. To compare it with our analysis from above, we can interpret σ as the confinement radius of physical mass of the object. For the case of a spherical source mass of radius R the most conservative bounds on decoherence are then obtained by assuming a homogeneous density distribution over the whole physical object, i.e.[5] $\sigma \approx R$. In that case, entanglement generation is therefore limited to distances $d < \Delta x + 0.85R$. For small delocalization $\Delta x \ll R$ this condition cannot be fulfilled in an actual experiment, since the physical boundaries of the spheres require $d > 2R$. For large delocalization $\Delta x \to \infty$ they find the critical distance for entanglement generation to be $d_c \approx 2.21\sigma$. Even though this allows for two physical spheres to be separated (by surfaces distances on the order of 10% of the radius), the additional requirements due to electromagnetic shielding and image-charge localization will unavoidably restrict the available superposition size to $\Delta x \ll d, 2R$, and hence the wanted parameter regime of large delocalization $\Delta x \to \infty$ cannot be realized in an actual experiment.

It is interesting to note that instead of parametrizing physical mass distribution, σ can also be introduced as a free phenomenological parameter that measures the spatial resolution of a continuously monitored mass density [20]. In this version of the Diósi–Penrose model, σ is not bounded by the physical size of the object and the simple argument presented here does not apply. In fact, Trillo and Navascués provide an explicit example for entanglement generation by the Diósi–Penrose model for $\sigma \gg R$ [34]. There are, however, constraints on σ from other

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[3]Two implicit assumptions are made: (i) since Γ_d is the local, single-particle decoherence rate, we assume that the contributions to decoherence from 2-particle dynamics (computed e.g. in [34]) only *add* to the overall system decoherence, hence making Γ_d a conservative lower bound; (ii) we assume the validity of current laws of physics, in particular Newton's law down to the short distances relevant for such experiments, and linearity of quantum theory for non-gravitational interactions [35]. This can be tested in independent experiments.

[4]For a rigorous analysis we note that Eq. (1) is obtained via Taylor expansion in $\Delta x/d$ and hence does not hold for arbitrary Δx. A full analysis has been provided in [34] and is discussed below.

[5]This is only an approximation as the analysis provided in [34] assumes a Gaussian distribution with no cut-off at the physical boundary of the sphere.

experiments, most notably precision measurements of gravity at short distances.[6] For example, Lee et al. [26] have performed percent-level measurements of Newton's constant at separations down to 50 μm, thereby placing a bound $\sigma \lesssim 50\,\mu\text{m}$. This bound is still less strict than $\sigma \le R$, but already sufficiently strict to prevent entanglement from being generated in the case study of [34]. It hence leaves an open challenge for both theory and experiment to either exploit or close this loophole of this version of the Diósi–Penrose model.

3. Conclusion

In conclusion, even though gravitational (collapse) models *à la* Diósi–Penrose can allow for gravitational entanglement [34], the strict physical boundary conditions imposed by the actual implementation of any such gravitational quantum sensing experiment likely prevent this from happening. This is because table-top gravity experiments require both (i) extended physical source masses that — in contrast to point masses — cannot penetrate each other, and (ii) electromagnetic shielding to isolate gravity as the relevant coupling mechanism. In a broader context, this discussion contributes to the still debated question "what do we learn from observing entanglement generated by gravity?" beyond the original motivation as a phenomenon "which the classical theory [of gravity] (without quantization) is unable to explain" [11] (see also [35–39]).

Declaration of interests

The author does not work for, advise, own shares in, or receive funds from any organization that could benefit from this article, and has declared no affiliations other than their research organizations.

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