Questioning universal decoherence due to gravitational time dilation

To the editor — The interface between gravitation and quantum theory is a fascinating subject. However, it is also riddled with subtleties, and slight confusion can easily lead to questionable conclusions. A striking example in this regard is provided by the work of Pikovski *et al.*[1], in which it is claimed that gravitational effects generically produce a novel form of decoherence for systems with internal degrees of freedom, which would account for the emergence of classicality. The effect is supposed to arise from the different gravitational redshifts suffered by such systems when placed in superpositions of positions along the direction of the gravitational field. There are, however, serious issues with the arguments of the paper.

First, the results of ref. 1 cannot be right in light of the equivalence principle, which is valid, by construction, in the frameworks used. This is because the only external force acting on all studied systems is generated by a gravitational field, and no spacetime curvature effects are relevant. As a result, the situations analysed are equivalent to ones without gravity, in which an accelerated observer studies free, isolated systems. Clearly, such scenarios cannot lead to decoherence as, without gravity, there is nothing to cause it. Moreover, as the systems described in ref. 1 are subject to gravity, they will not remain static when placed in a superposition of fixed positions. Of course, one could achieve this by including a compensating force generated by an external device, and this additional interaction may lead to decoherence, but this effect cannot be ascribed to gravity.

Next, notice that a central premise of the analysis presented in ref. 1 asserts that the system's internal energy contributes to its effective mass, which thus can have more than one value. However, ordinary non-relativistic quantum mechanics cannot deal with such situations[2], a fact ignored by Pikovski *et al.*[1] in their free use of such a framework.

Finally, the widespread belief that decoherence can explain the quantum-to-classical transition, which is key in the analysis of the paper, is unjustified[3]. The confusion arises from the fact that the density matrix of an improper mixture (which represents the partial description of a subsystem that is part of a larger system in a pure state) has, after decoherence takes place, the same form as that of a proper mixture (which represents an actual ensemble of systems)[4]. It does not, however, follow from such formal similarity that the two physical situations are identical. Therefore, even if the reduced density matrix for the centre of mass of the systems considered in ref. 1 has the same form as a statistical mixture, it does not follow that their physical situation is indistinguishable from that of an ensemble; the centre of mass continues to be as entangled and delocalized as it was before the alleged decoherence took place.

We conclude, from all this, that the claims of Pikovski *et al.* in ref. 1 are invalid. An in-depth analysis of the results and claims in ref. 1 is provided in ref. 5. ❐

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Reply to 'Questioning universal decoherence due to gravitational time dilation'

Pikovski *et al.* reply — The claims in the comment by Bonder *et al.*[1] are incorrect and are rooted in a confusion of basic aspects of classical relativity and quantum mechanics. Here we briefly address the mistakes and concerns.

First, the authors claim that our results are wrong "in light of the equivalence principle" and that a uniformly accelerated frame "cannot lead to decoherence as, without gravity, there is nothing to cause it." On the contrary, the equivalence principle predicts that both the gravitational potential and uniform acceleration lead to the same time dilation and thus to the same decoherence, as they are described locally by the same metric. This is also highlighted in Fig. 2 in our manuscript[2]. Equation (4) in our paper shows that decoherence is a simple function of time dilation between the superposed paths, which can for example be stationary (as explicitly considered in our paper) or in free-fall (to which the comment refers). As long as time dilation is present between the superposed paths, decoherence will take place, which in no way contradicts the equivalence principle.

The authors correctly point out that to measure gravitational time dilation, clocks should be kept at a fixed position. This is explicitly taken into account in our equations (5) and (6). But time dilation is not caused by and does not depend on the exact nature of the trapping potential necessary to fix the positions of the clocks. Quite the opposite: different trapping potentials will result in the same measured time dilation if they keep the system at the same height, a key principle of relativity. In the same way, decoherence from gravitational time dilation does not depend on the specific force necessary to perform the experiment. Note also that, as recently shown by Gooding and Unruh[3], time dilation can produce decoherence even in the absence of any interaction other than gravity.

Next, the authors worry that "the system's internal energy contributes to its effective mass, which thus can have more than one value." This worry is unjustified and contradicts experimental evidence: superpositions of internal energy levels are routinely employed in a vast range of technologies. Atomic clocks are based on precisely such superpositions and were recently utilized to measure time dilation[4]. If internal energy did not contribute to the mass for a superposition state, as the authors claim, atomic clocks would not be affected by time dilation, contrary to what is observed. The confusion of the authors seems to stem from Bargmann's result: superpositions of solutions to a non-relativistic Schrödinger equation with different masses are not invariant under the Galilei group, and therefore unphysical in a Galilei-invariant theory in Euclidean spacetime. But this mass-superselection rule to which the comment refers does not hold in relativistic quantum theory[5] and does not apply to our work. We consider time dilation and thus relativistic quantum systems that are obviously not invariant under the Galilei group. The derived Hamiltonian is the time-like component of the relativistic momentum four-vector and describes a particle on a Lorentzian spacetime manifold. The Hamiltonian treatment in first quantization is standard to describe relativistic corrections to single particles, where high-energy quantum field theory effects can be neglected, but where relativistic corrections from the background spacetime can enter[6]. The resulting Schrödinger equation includes relativistic corrections and is different from the non-relativistic one, as derived in the Methods section of our paper (which also includes a derivation based on a quantum field model).

Finally, the authors write that decoherence cannot explain the quantum-to-classical transition, as a subsystem is just a part of a larger, pure system, and thus constitutes an "improper mixture". Whereas it is entirely correct that we consider subsystems of larger, pure systems, this is always the case within the field of decoherence. For the study of how coherence of a subsystem is affected by correlations with a large, inaccessible environment, which is the goal of our work, only the density matrix of the subsystem is relevant, and not whether it stems from a "proper" or "improper mixture". Thus the results of our work do not hinge on an alleged physical difference between proper and improper mixtures, which lies outside quantum theory and outside the scope of our work.

A more detailed discussion of the basic concepts that enter our work can be found in ref. 7.

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