Comment on "Universal decoherence due to gravitational time dilation"

Yuri Bonder,[1] Elias Okon,[2,*] and Daniel Sudarsky[1]
[1]*Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México*
Apartado Postal 70-543, México D.F. 04510, México
[2]*Instituto de Investigaciones Filosóficas, Universidad Nacional Autónoma de México*
Circuito Maestro Mario de la Cueva s/n, México D.F. 04510, México

The interface between gravitation and quantum theory is a fascinating subject. It has inspired, over the years, a constant flow of novel and exiting ideas, many of them adventuring beyond standard quantum mechanics or general relativity [1–4]. The topic is also one riddled with subtleties, where slight confusion can easily lead to erroneous conclusions. Consider in this regard the seemingly paradoxical question of the emission of photons by a charged particle undergoing constant proper acceleration, as seen by an equally accelerated observer, in view of the equivalence principle: why would a static charge in a static gravitational field radiate? [5–7]; the alleged violation of the equivalence principle by oscillating neutrinos [8, 9]; the fierce controversy surrounding the claim that the gravitational redshift can be measured with an atom interferometer [10–12]; or the proliferation of incompatible opinions regarding the validity of the equivalence principle in quantum settings [13].

Another dramatic case in the area where oversight of nuances prompted questionable conclusions is provided by the recent article "Universal decoherence due to gravitational time dilation" [14]. There, it is claimed that gravitational effects generically lead to a novel form of decoherence for systems with internal degrees of freedom, which explains 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. A noteworthy aspect of this claim is that, in contrast with other speculative ideas in this realm, it is supposed to follow directly from standard quantum theory together with standard aspects of gravitation as provided by general relativity. Needless to say, a result of such characteristics would be extraordinary. Unfortunately, as we argue in this comment, the analysis of [14] is mistaken.

The arguments against the conclusions in [14] can be divided in two groups. The first group concerns several subtle issues in the overlap of the quantum and the gravitational realms. The second group, which is not at all specific to the claims in [14], has to do with the alleged ability of decoherence to explain the quantum-to-classical transition. In this brief note we only mention the objections that, in our opinion, are the most relevant. We start with those of the first group.

To begin with, we consider the example presented in [14] where a system with internal degrees of freedom, modeled as a family of harmonic oscillators, is placed in a superposition of being at two different heights in a uniform gravitational field. This scenario, it is claimed, leads to decoherence. Note however that according to the equivalence principle, the situation under consideration is physically equivalent to that in which an accelerated observer in a gravity-free region of space studies such a delocalized system. It is clear that, in that case, there is no possibility for the claimed decoherence to occur, as there is simply nothing to attribute it to (recall that gravity has completely disappeared from the picture). Notice, furthermore, that the equivalence principle issue is not only problematic for the simple example considered above but for all the results of the paper (where the effects that are actually associated with spacetime curvature are neglected). This is because the theory of quantum fields in curved spacetime, a framework that supposedly underscores the results of [14], is, by construction, fully compatible with the equivalence principle. We can then conclude, in view of the equivalence principle, that there must be something wrong with the results of the article.

The above observations led us to realize that the situation at hand is more complex than what is considered in [14]. If the quantum mechanical system in question is subject to gravity (as described, for example, by a static observer on the surface of the Earth), then, it will fail to remain static (in the appropriate quantum mechanical sense). Moreover, if the system is initially prepared in superposition at the locations x_1 and x_2, it will also fail to remain in the superposition of such locations. In fact, if one wants to have the system static at those fixed points, one would need to exert a compensating force on the system by means of some external device which should be described by the appropriate interaction term in the Hamiltonian. Only then will the system remain in the location it was initially placed, or in the corresponding superposition thereof. Of course, it is possible that the interaction of the delocalized system with the external device that keeps it static may lead to decoherence. However, it is clear that such result will depend on the exact nature of the interaction between the system and the external device and that it has nothing to do with gravity. All these crucial observations are completely disregarded in [14].

---

[*] eokon@filosoficas.unam.mx

From the previous discussion it follows that in order to analyze the issue of interference between two localized components of a superposition, one needs to be very careful in considering the concrete experimental situation where one would attempt to detect it. For instance, if the wavepackets are to be brought together in order to use a single detector for the observables associated with the internal degrees of freedom, the evolution taking these two wavepackets to a single position must be taken into account. Only then would one be able to decide whether interference would occur or not. Of course, due to the equivalence principle, a consistent treatment of the situation should lead to the same result whether it is carried out in the frame where there is gravitation or in the one without it. Clearly this implies, as we pointed out above, that, at the end of the day, the results are to be determined not by gravity but by the external device that is used to control the motion of the system.

The next issue arises from the fact that a key premise of the analysis presented in [14] asserts that the system's internal energy contributes to its effective mass. As a result, the effective mass of the system can have more than one value. Notice however that, due to Bargmann's super-selection rule [15], ordinary nonrelativistic quantum mechanics cannot deal with such situations. Therefore, it seems that the scenario considered in [14] calls for a nonstandard version of quantum mechanics suitable for dealing with superpositions of states with different masses. This issue is subtle because, although ordinary quantum mechanics can be derived from relativistic quantum field theory, where no such super-selection rule exists, the various steps in the approximation, which are certainly nontrivial [16], lead to the appearance of that restriction. Of course, none of this is considered in [14].

Finally, on top of all this, there is the reliance of the analysis on the alleged ability of decoherence to explain the quantum-to-classical transition. So, let us grant, for the sake of argument, the claim that gravity produces decoherence (*i.e.*, that it manages to entangle the state of the position of the center of mass of a system with that of its internal degrees of freedom). Is that enough to claim that this explains why we do not experience such objects as delocalized? Or, to place the question more generally, is decoherence sufficient in order to explain the emergence of classicality? As it has been convincingly argued before [17, 18], the answer is no. The main reason is that, even if the reduced density matrix for the center of mass, obtained by tracing over the internal degrees of freedom, has the same form as that which represents a *statistical mixture* in which the center of mass is in *either* one or the other of the locations of the superposition, it does not follow that the *physical* situation is identical as well. In fact, the physical situation is extremely different since by taking the trace (or by simply ignoring the internal degrees of freedom) nothing physical can happen, so the physical state of the center of mass is as entangled and delocalized as it was before.

The central point is that one should be careful to distinguish a *proper* mixture, which represents an actual ensemble of systems, each of which has been prepared to be in a different but well-defined state, from an *improper* mixture, which represents the partial description, as provided by the reduced density matrix, of a subsystem which is part of a larger system that, as a whole, is in a pure state (see for example [19]). Furthermore, in order to claim that for all practical purposes a system described by an improper mixture does behave as one described by a proper one (as it would be needed, in addition to decoherence, in order to truly explain the emergence of the classical regime), it is critical to recognize that one needs to assume a breakdown of unitarity during measurements. It seems, then, that it is not decoherence but such a breakdown of unitarity that does the work. One can see some of these issues arising in the following simple example. In a EPR-B situation, by tracing over the spin degrees of freedom of one of the particles, one obtains, for the other particle, a fully decohered density matrix (*i.e.*, one that is diagonal). However, it is clear, given Aspect's experiments confirming the violation of Bell's inequalities [20–22], that one cannot assume that such particle has a definite (even if unknown) value for its spin before a measurement takes place. That is, decoherence is not equivalent to classicality.

We conclude from all this that the claims of [14] are invalid.

ACKNOWLEDGEMENTS

We acknowledge partial financial support from DGAPA-UNAM project IA400114 (EO) and CONACyT project 220738 (DS).

---

[1] Penrose R. *The Emperor's New Mind* (Oxford Univ. Press, Oxford, 1989).
[2] Penrose R. *Gen. Rel. Grav.* **28**, 581 (1996).
[3] Diosi L. *Phys. Lett. A* **105**, 199 (1984).
[4] Diosi L. *Phys. Lett. A* **120**, 377 (1987).
[5] Higuchi A., Matsas G. E. A., & Sudarsky D. *Phys. Rev. D* **45**R, 3308, (1992).
[6] Higuchi A., Matsas G. E. A., & Sudarsky D. *Phys. Rev. D* **46**, 3450 (1992).
[7] Peña I., Chryssomalakos C., Corichi A., & Sudarsky D. *Phys. Rev. D* **72**, 084018 (2005).

[8] Ahluwalia D. *Gen. Rel. Grav.* **29**, 1491 (1997).
[9] Chryssomalakos C. & Sudarsky D. *Gen. Rel. Grav.* **35**, 605 (2003).
[10] Müller H., Peters A., & Chu S. *Nature* **463**, 926 (2010).
[11] Wolf P. et al. *Class. Quantum Grav.* **28**, 145017 (2011).
[12] Sinha S. & Samuel J. *Class. Quantum Grav.* **28**, 145018 (2011).
[13] Okon E. & Callender C. *Euro. Jnl. Phil. Sci.* **1**, 133 (2011).
[14] Pikovski I., Zych M., Costa F., & Brukner C. *Nature Phys.* doi:10.1038/nphys3366 (2015).
[15] Bargmann V. *Ann. Math.* **59**, 1 (1954).
[16] Y. Bonder et al. *Phys. Rev. D* **87**, 125021 (2013).
[17] Adler S. L., *Stud. Hist. Phil. Mod. Phys.* **34**, 135 (2003).
[18] Janssen H. M. Sc. Thesis, Radboud University Nijmegen (2008).
[19] d'Espagnat B. *Conceptual Foundations of Quantum Mechanics* (Addison Wesley, 2nd. edition, 1976).
[20] Aspect A., Grangier P., & Roger G. *Phys. Rev. Lett.* **47**, 460 (1981).
[21] Aspect A., Grangier P., & Roger G. *Phys. Rev. Lett.* **49**, 91 (1982).
[22] Aspect A., Dalibard J., & Roger G. *Phys. Rev. Lett.* **49**, 1804 (1982).