Non-equilibrium quantum thermodynamics of gravitational collapse models

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Abstract: By focusing on the Diosi-Penrose models, we provide a non-equilibrium quantum thermodynamic assessment of the tenability of gravitationally-induced mechanisms that are allegedly responsible for the quantum-to-classical transition

One of the most important open problems in theoretical physics is how to reconcile gravity and quantum mechanics. Both theories work well within their respective domains of validity, but finding a unified description from which both can be derived remains a profound challenge. The standard approach is to assume that gravity, like other fundamental interactions, should be quantized. Despite extensive efforts in this direction, a fully developed quantum theory of gravity remains elusive. A radically different approach is to consider to not quantize gravity and instead assuming that gravity plays a fundamental role in the wave function collapse. The idea is to modify quantum mechanics by introducing a spontaneous collapse related to gravity [1]. When gravitational effects become significant, quantum coherences in space should reduce, leading to a breakdown of the superposition principle [2]. Thus, a new approach to merging gravity and quantum theory emerges, which not only attempts to reconcile the two but also provides a solution to the quantum measurement problem [3].

The first proper collapse model who relates spontaneous wave function collapse to gravity was introduced by Diosi [4,5]. The timescale for the collapse of a spatial superposition predicted by this model coincides with that later proposed by Penrose [2], and for this reason the two proposals are now commonly referred to as the Diosi-Penrose (DP) model. This modifies the Schrödinger equation by introducing terms that predict wave function collapse in space [5, 6]. It has been shown that whenever collapse is introduced into the dynamics, it inevitably comes with an associated diffusive behavior [7], which has been exploited to place experimental constraints on the free parameter of the model, through experiments involving bulk matter [8] and radiation emission from germanium [9], which currently provide the most stringent bounds on the free parameter of the model [10].

In the DP model, diffusion also manifests as a steady increase in energy of the center of mass, even for isolated systems. This violates energy conservation, albeit at a level too small to be detected in current experiments for a large set of values of the free parameter of the model. While violations of energy conservation may be tolerable from a phenomenological perspective, the nonphysical nature of a persistent energy increase is problematic even within the framework of an effective model; one would expect a system to thermalize with the noise that induces collapse, rather than exhibit an unbounded energy growth. To address this issue, two dissipative extensions of the DP model have been proposed. These models introduce a mechanism that allows the system to reach thermal equilibrium with the collapse-inducing noise, hence mitigating the energy increase problem and leading to a more consistent dynamics from a thermodynamical point of view. This is precisely what we discuss in this work: ***we characterize thermodynamically the DP model and its dissipative generalization. We show that the dissipative extension of the DP model adheres to the Clausius law of thermodynamics, leading to a physically consistent thermal equilibration, in contrast to the original DP model in which thermal equilibrium is never reached and no violations of the Second law are witnessed only for an infinite temperature noise field.*** To reach these conclusions, we study the entropy production rate of the dynamics, a quantity intimately related to the Second law, over time exploiting the phase-space picture of the dynamics.

References

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