Quasiprobability thermodynamic uncertainty relations

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The thermodynamic uncertainty relation (TUR) is a central trade-off relation in nonequilibrium thermodynamics, connecting dissipation, current, and fluctuations. While many classical and quantum extensions have been developed, a basic difficulty remains in the quantum regime: dynamical fluctuations of a general observable are not straightforward to define because observables at different times need not commute. Existing approaches typically focus either on jump-like quantities accessible through full counting statistics, or on two-point measurement schemes that erase the initial coherence of the observable of interest. This leaves open the question of how far thermodynamic trade-off relations remain universal in genuinely quantum situations, where noncommutativity and coherence are essential.

In this talk, I present a quantum extension of the TUR in Markovian open quantum systems in which the fluctuation of an observable's change is characterized by the Terletsky–Margenau–Hill quasiprobability. This quasiprobability is a natural quantum analogue of a classical joint probability for two-time statistics and retains the effects of initial coherence without introducing invasive projective measurements. Using this framework, we derive a universal short-time TUR that bounds the entropy production rate from below by the ratio between the squared dissipative current and the short-time fluctuation of an arbitrary observable. In this sense, the result provides a complementary quantum TUR: rather than focusing on exchanged charges associated with jumps, it applies directly to intrinsic observables represented by Hermitian operators.

I then discuss what kinds of genuinely quantum behavior are required to beat classical limitations. The quasiprobability formalism reveals that anomalous enhancement of the output-to-dissipation ratio is impossible unless the dynamics exhibits either negativity of the quasiprobability or a non-classically enhanced escape rate. These conditions are basis-independent and, in an appropriate sense, stricter than merely having large quantum coherence. As an illustration, I show a model that can display a dissipationless heat current, a phenomenon forbidden in classical settings, and explain why some highly coherent states still fail to realize it when the relevant quasiprobability does not exhibit the necessary anomalous features. These results clarify that the key resource behind the violation of classical thermodynamic limitations is not coherence alone, but more specifically the nonclassical structure encoded in quasiprobabilities.

Reference:

K. Yoshimura & R. Hamazaki, Phys. Rev. Lett. 136, 120406 (2026).