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Nonequilibrium Steady States of Quantum Many-Body Systems: Heat Transport and "Hot Entanglement"*

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Abstract Stationary states play a specially important role for nonequilibrium systems (NESS) as equilibrium states in canonical ensembles for statistical mechanics. Existence and uniqueness of a NESS for *classical* many body systems is a main theme of research by mathematical physicists for decades [1]. Answering this question for *quantum* many-body systems poses a major challenge for the present. While mathematical proofs of theorems for these basic issues are of great importance, being able to follow how these quantum systems evolve in time explicitly provides additional insights into its nonequilibrium properties. In a recent work [2] we use functional methods [2] to derive the *quantum stochastic equations* (master, Langevin, Fokker-Planck) for a prototypical quantum open system -- a harmonic chain in contact with two heat baths -- and by examining the energy flux relations in the open system, show the existence of NESS at late times. The functional method when combined with perturbative techniques can be used to explore *quantum transport problems in nonlinear systems* [3][4].

As an application, a topic in quantum thermodynamics of theoretical interest and relevant to quantum information processing is "hot entanglement" [5] -- whether quantum entanglement can be maintained up to some high temperature. Galve et al [6] show that entanglement can be kept to a high temperature if the intra-system coupling is parametrically driven. To discern the true physical causes of a system's ability to sustain quantum entanglement at high temperatures we begin with two generic cases where the coupling between the two oscillators in the system is a constant: A model system S of two coupled oscillators interacting 1) with a common thermal bath [7] and 2) when each oscillator is coupled to its own bath, but kept at different temperatures [8]. The difference is that after S is fully relaxed, assuming weak coupling with the bath(s), the quantum system in Case 1 approaches thermal equilibrium, while in Case 2 approaches a nonequilibrium steady state (NESS). The entanglement behaviors in these systems are found to be very different. At high temperatures, in both cases, entanglement in systems with constant coupling are shown to be insignificant. Entanglement in quantum driven systems may differ.

*Based on joint work [2],[7],[8] with **J. T. Hsiang,** *Physics Dept, Fudan University, Shanghai, China*

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