

PhD Thesis Defense ANIELLO LAMPO 'Quantum Brownian Motion Revisited: Extensions and Applications'

ANIELLO LAMPO

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ANIELLO LAMPO

Quantum Optics Theory

ICFO-The Institute of Photonic Sciences

Quantum Brownian motion represents a paradigmatic model of open quantum system, namely a system which cannot be treated as an isolated one, because of the unavoidable interaction with the surrounding environment. In this case the central system is constituted by a quantum particle, while the bath is made up by a large set of uncoupled harmonic oscillators. In the original model, the interaction between the system and the environment

shows a linear dependence on the particle position. Such a particular form corresponds to a homogeneous environment, inducing a damping and diffusion which depends on the state. This is not the most general situation: often the environment shows an inhomogeneous character given by a space-dependent density, involving a non-linearity in the coupling with the central system. One of the main motivations of the thesis is the study of quantum Brownian motion in presence of this non-linear coupling. In particular we focus on the case in which the bath-particle interaction depends quadratically on the position of the latter. There exist several techniques aimed to treat the physics of the model. For instance one could consider the master equation, namely an equation ruling the temporal evolution of the state of the Brownian particle, here represented by its reduced density matrix. We derive such an equation in the Born-Markov regime and look into its stationary solution, studying its configuration in the phase space. For a non-linear quadratic coupling the stationary state may be approximated by means of a Gaussian Wigner function, that experiences genuine position squeezing (i.e. the position variance of the particle takes a value smaller than that associated to the Heisenberg principle, although this is fulfilled) at low temperature and as the coupling with the bath grows. However, the Born-Markov master equation is not the most appropriate tool to investigate the regime in which squeezing occurs, since the underlying hypothesis in general fail at strong coupling and low temperature, leading to violations of the Heisenberg principle. To overcome this problem we recall alternative methods, such as a Lindblad equation, namely a master equation constructed to preserve the positivity of the state at any time, and Heisenberg equations. In particular we employ the Heisenberg equation formalism to explore the behavior of the Bose polaron, i.e. an impurity embedded in a Bose-Einstein condensate. This experimentally feasible system attracted a lot of attention in the last years. We derive the equation of motion of the impurity position showing that it shows the same form of the famous equation derived by Langevin in 1909 in the context of classical Brownian motion. The main difference lies in the fact that the impurity Langevin-like equation for the impurity carries a certain amount of memory effects, while the original one was purely Markovian. An important part of the work is devoted to the solution of the motion equation for the impurity, in order to calculate the position variance that can be measured in experiments. For this goal we distinguish the case in which the impurity is trapped in a harmonic potential and that where it is free of any trap. In the latter case the impurity the position variance exhibits a quadratic dependence on time (i.e. ballistic diffusion), as a consequence of memory effects. When the impurity is trapped in a harmonic potential it approaches an equilibrium state localized in average in the middle of the trap. Here, at low temperature and for certain values of the coupling strength we detect genuine position squeezing. When we consider a gas with a Thomas-Fermi profile we find that such an effect is improved if we make the gas trap tighter. Genuine squeezing plays an important role in the context of quantum metrology and opens a wide range of possibility to design new protocols, such as the quantum thermometer.

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Thesis Advisor: Prof Dr Maciej Lewenstein

