Quantum Stochastic Dynamics : from Qu-bits to Many-Body Physics

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Stochastic processes enter Quantum Mechanics from different corners. They arise from a measurement perspective since, upon monitoring, quantum systems evolve randomly due to information readout and random back-action, and have echoes in fundamental issues in Quantum Mechanics. They manifest themselves in Quantum Mechanics from an out-of-equilibrium statistical physics perspective, since the evolution of open quantum systems acquires some randomness through their interaction with external reservoirs. Stochastic processes, whether classical or quantum, are also instrumental in quantum information processing through measurement based, or coherent, quantum control as the interaction of quantum devices with the driving inputs are to a good approximation modelled by quantum noise.

The different facets of this relationship are actively explored today. Quantum monitoring theory led in the '90s to the notion of quantum trajectory, now a key concept and a practical tool in applied quantum control. Developing rigorous methods for the control of quantum systems is currently a very active field of theoretical physics and of mathematics. These theoretical developments go hand in hand with recent experimental progress on quantum state manipulations, say for manipulating photons or Qu-bits in cavities, and are needed for reliable quantum information processing. In parallel, prompted by an impressive set of experimental advances in many-body quantum systems, say using cold atoms in optical lattices, good methodological approaches to deal with closed many-body quantum systems are being developed. It is therefore a timely opportunity to do quality mathematical physics inspired by experimental physics.

Proposal Overview:

The present proposal grows out of these developments. It is directed towards developing a sharp theoretical understanding of open, out-of-equilibrium, many-body quantum systems. It aims in particular at answering basic questions about those systems such as: How profoundly does information readout, or dynamical interactions with reservoirs, affects their dynamics? How is transport in those systems consequently modified? How effective is quantum information or entanglement spreading? How efficient is information reading? What distinguishes and characterises randomness induced by monitoring from that induced by reservoir interactions? How do those fluctuations affect transport, propagation and readout? Are there efficient and precise descriptions of their statistics? Also, how to transfer stochastic methods in quantum settings? Can the methodological tools developed to answer these questions find applications in companion scientific fields?

The proposal grows out from theoretical results about closed, isolated, quantum systems that have recently flourished, with a better perception of the roles of integrability, chaos or disorder in thermalisation, or in its absence. In critical or integrable models, including the Lieb-Liniger model which is known to describe accurately gases of cold atoms in quasi-one-dimensional traps, a good understanding has been obtained with a precise description of entanglement dynamics, of quenched dynamics, as well as of transport. However, these understandings are not yet as refined as those available for analogous classical phenomena, and furthermore, these results are restricted to closed, mostly ballistic, systems with non dissipative dynamics.

The aim of this project is to take a new step and to extend our understanding of out-of-equilibrium quantum dynamics to open dissipative many-body systems in contact with their environments, be they external reservoirs or monitoring devices. A special emphasis is put on information readout, information and entanglement propagation, on transport properties, and their fluctuations.

Stochasticity plays a prominent role in understanding these systems, via quantum monitoring or via dynamical contacts with reservoirs. To progress in their understanding requires extending and creating concepts, tools and applications of stochastic processes in Quantum Mechanics, more generally in quantum many-body out-of-equilibrium dynamics and their inter-disciplinary applications. Traditionally, research in classical and quantum systems, at or away from equilibrium, has remained mostly separated, the two communities having slightly different goals and using distinct methodologies. Recent theoretical and experimental developments in both areas show that it is time to bridge the gap.

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