Research Statement

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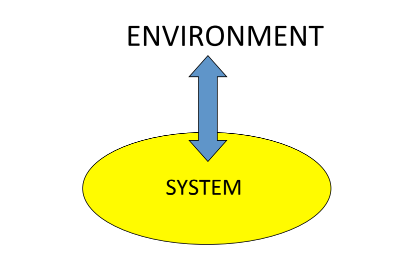
Quantum mechanics has already influenced our lives to an astonishing degree. Consider, for example, the fact that our understanding of transistors, the basic building block of modern computers, is derived from the basic principles of quantum mechanics, or that global positioning systems would not be possible without quantum mechanics. Nevertheless, it seems inevitable that a second quantum revolution is coming, a revolution that envisages the use of truly fundamental quantum effects such as quantum superposition and entanglement to build devices of the future that fundamentally surpass the performance of any current device. The most well-known example is, of course, the quantum computer, but it is also expected that quantum mechanics will (and, in some cases, already has) allow us to construct extremely accurate measuring instruments, highly efficient artifical light-harvesting systems, and communication systems with unbreakable encryption.

All the novel quantum technologies rely on understanding the dynamics of realistic quantum systems given their initial state. For closed systems that is, 'small' quantum systems not interacting with anything else, we already know the answer, at least in principle - we simply use the Schrodinger equation. But closed systems are an idealization in physics; realistic physical systems are always interacting with their environment, and are, therefore, 'open' systems. For example, a hot object cools down since it is able to lose energy to its surroundings. However, this is not the only effect of the environment for small, microscopic systems. Open *quantum* systems also undergo what is called 'decoherence'. The principle of superposition in quantum mechanics says that given two possible states of a system, the superposition of the two states is also a possible state of the system. Decoherence then refers to the decay of this superposition: the superposition is destroyed via the interaction with the environment. Decoherence thus adds a further layer of complexity to the study of open quantum system dynamics.



An open system - the system interacts with its environment

I should also point out that the study of open quantum systems is important not just from the perspective of emerging quantum technologies. Open quantum systems lead to a better understanding of many processes occurring in nature, such as spontaneous emission in excited atoms, electron transfer in photosynthetic complexes, and quantum statistical processes in the early universe and black holes. Futhermore, open quantum systems are fundamentally important to study the thermodynamic properties of quantum systems since the canonical Gibbs distribution fails for small quantum systems that are interacting strongly with their environment - this is why quantum open systems are central in the emerging field of quantum thermodynamics. Finally, decoherence has been used to explain why we do not routinely observe superposition states in the classical world that we are used to. The answer is that most quantum states rapidly decohere via the system-environment interaction. It is only a few special states (referred to as 'pointer states') that we are actually able to observe in practice. In short, open quantum systems impact many different interdisciplinary areas such as quantum optics, control theory, condensed matter, quantum information, and chemical physics.

My research in this broad area of open quantum systems largely deals with **two** interrelated questions: first, **what are the dynamics of realistic open quantum systems**? Second, **how can we control and make use of such quantum systems**? I will address these very briefly one by one.

Regarding the first question, it should come as no surprise that solving for the dynamics of open quantum systems is a *hard* problem, and in spite of considerable effort over the years as well as a few exactly solvable cases, we still do not know, in general, what is the equation of motion (known as the 'master equation') for a given quantum state. Given the complexity of the problem, a large number of approximations and assumptions have to be made. Yet it has now been realized that for many physical systems, these approximations are not always valid. For example, it is commonly assumed that the system and environment are weakly interacting and that the environment has a short memory time. But for many systems, such as atom-cavity systems and superconducting systems, both of these approximations are not valid. It is then of vital importance to understand not only when a given approximation is justified, but also to design techniques and methods for dealing with such situations.

Once we have a reasonable idea of how a realistic quantum system behaves, the second problem is to engineer the system in a suitable manner in order to achieve some desired objective. For instance, one can consider applying electromagnetic fields to the system to change the state of the system in a controlled manner. A similar problem has been studied in classical physics and engineering for a long time under the umbrella of *control theory*, and a wide variety of results have been obtained. Classical control theory and quantum control theory, however, differ in at least two aspects. First, due to the superposition principle, quantum systems tend to live in a much larger space, making solutions much harder. Second, measurements in quantum mechanics have a very different role. In classical physics, we can always, at least in principle, design the measurement such that any disturbance induced by the measurement is negligible. The measurement result can then be used to obtain information about the present state of the system and thereby control its future state. Quantum mechanically, however, we cannot generally ignore the disturbance induced by any measurement we perform. Thus, the role of measurements needs to be understood properly. In fact, a large part of my research deals with what happens to quantum system if it is subjected to rapid measurements repeatedly. Another major thrust of my research is to design control fields such that the quantum state is protected for prolonged periods of time. The basic idea, motivated from spin echoes in nuclear magnetic resonance, is that by applying control pulses, the evolution of the quantum system can be repeatedly reversed. These reversals then lead to the cancellation of any noise acting on the system, provided that the control fields are applied fast enough. For example, one of my recent works has studied the protection of quantum states in a chain of qubits, the basic building blocks of a quantum computer.

Finally, I should also emphasize that both theory and experiment play a key role in quantum open systems and their control. Moreover, sometimes theory leads experiment, while at other times, the opposite is the case. For example, quantum control theory predicted particular ways of applying control fields in order to achieve more efficient protection of the system from the environment, and these predictions were duly verified in the laboratory. On the other hand, the surprising experimental discovery of highly efficient electron transfer in photosynthetic complexes has led theorists to revise their open system models. Keeping this in mind, I expect to build strong collaborations with experimentalists in the future.