7

Conclusion and future directions

This thesis has investigated various facets of nonclassicality in subatomic and quantum optical systems and their interplay with the underlying dynamics. An intuitive way to define nonclassicality is a departure from the basic assumptions on which a classical theory is based. An important development in this direction has been the Leggett-Garg type tests, involving correlations of measurements on a system at different times, and stand as one of the hallmark tests of quantum mechanics against classical predictions. These tests are based on the notion of (a) *realism* i.e., a system, during its time evolution, is at any given time in one of the available states, and (b) *noninvasive measurability*, which means that it is possible, in principle, to determine which of the states the system is in, without affecting the system's subsequent dynamics. This problem is studied here on a number of problems relevant to subatomic physics, in particular, neutral mesons and neutrino oscillations.

The nonclassicality, in the context of quantum optics, is defined in terms of nonclassical states of light, i.e., the quantum states having negative values of Glauber-Sudarshan P function and are of profound importance from the perspective of quantum information and technology. Typical examples of such states are entangled states, steerable states, squeezed states, and antibunched states. A cavity system embedded with two ensembles of two-level atoms was studied for various witnesses of nonclassicality and it was shown that the degree of nonclassicality can be controlled by system parameters.

The nonclassical behavior of light shows interesting features in Parity-Time ($\mathcal{PT}$) symmetric systems. The central idea of $\mathcal{PT}$-symmetric quantum theory is to replace the condition that the Hamiltonian of a quantum theory be Hermitian with the condition that it possess space-time reflection symmetry ($\mathcal{PT}$ symmetry). This allows us to construct and study many new kinds of Hamiltonians. These new Hamiltonians have remarkable mathematical properties and have recently been found useful in describing various physical phenomena. The interplay between $\mathcal{PT}$ symmetry and nonclassicality features such as entanglement and measurement induced disturbance was brought out. The $\mathcal{PT}$ symmetric dynamics was shown to enhance the degree of coherence and lead to maximal violation of LGIs such that the algebraic maximum is reached at the exceptional point.

Open Quantum System approach becomes indispensable while dealing with real physical systems. The most realistic picture of quantum dynamics is almost invariably non-Markovian, i.e., involves *memory* effects as a consequence of system-environment interaction. The thesis addressed the interplay of non-Markovianity with various facets of quantum information. Probing non-Markovianity via generalized measurements by mapping dynamics with measurements using positive operator valued measures was illustrated in this thesis.

Quantum channels are completely positive and trace preserving maps between the spaces of operators and describe processes like transmission of classical as well as quantum information.

Quantum information protocols are based on the fact that information is transmitted in the form of quantum states. In this context, the Open Quantum System effects become pertinent. The reliability of quantum channels for transmitting information is of profound importance from the perspective of quantum information. This naturally leads to the question as how well a quantum state is preserved when subjected to a quantum channel. A measure of quantumness of channels based on non-commutativity of quantum states that is intuitive and easy to compute, was proposed.

The investigations made in this thesis have lead to several new insights and problems which can be addressed in future. Some of these are:

1. To develop a better understanding of non-Markovian dynamics from the perspective of measurement. In this direction, one can exploit the fact that a projective made on a state subjected to noisy evolution, can be viewed as a noise induced POVM (projective operator valued measure) characterized by *bias* and *unsharpness* parameters which can reveal information about the nature of the underlying dynamics.

2. The maximal coherent behavior at exceptional point in a $\mathcal{PT}$ symmetric system waits for a clear explanation. One of the possible approaches would be to translate the $\mathcal{PT}$ dynamics into completely positive and trace preserving maps or quantum channels. This would also allow one to investigate the behavior of coherence in conjunction with the purity of such quantum channels.

3. Investigation of non-Markovianity using quantum channel capacity. The various existing measures of non-Markovianity are based on non-monotonic behaviour of certain quantities associated with the breakdown of the divisibility property. A departure from a monotonic behavior of the quantum classical capacities has been recently proposed to quantify the degree of non-Markovianity. It would be interesting to see the effect of various facets of non-Markovianity on the capacities of quantum channels compared to the corresponding Markovian ones.

4. To characterize the pseudo-Hermitian Hamiltonians from the perspective of coherent operations. It has been recently reported that the non-Hermitian dynamics generated by a $\mathcal{PT}$ symmetric Hamiltonian can act as a coherent operation, i.e., it can increase coherence in a maximally mixed state. Since $\mathcal{PT}$ symmetric systems form a class of a family of pseudo-Hermitian systems (in which the underlying symmetry is not necessarily $\mathcal{PT}$), it would be interesting to classify these pseudo-Hermitian Hamiltonians based to their capability of increase the coherence of a system.

5. It would be interesting to analyze the behavior of coherence under non-unitary dynamics by relaxing the semiclassical approximation and investigating the EPs of the underlying Lindbladian. The non-unitary dynamics has mostly been described by effective Hamiltonian approach by neglecting the *jump operators* in the master equation. However, recently, the behavior of EPs was first time described from the point of view of Lindbladian rather than the effective Hamiltonian. This approach is more robust and can reveal important insights regarding the behavior of various physical quantities around EPs in full open system scenario.

6. The measures of quantumness of qubit channels discussed in this thesis can be be generalized to higher dimensional systems.

7. It is well known that the quantum bound for temporal correlations in a Leggett-Garg test,

analogous to the Tsirelson bound for spatial correlations in a Bell test, strongly depends on the number of levels N that can be accessed by the measurement apparatus via projective measurements. This fact can be used to probe the dimensions of neutrinos system and make some statement about the existence of *sterile* flavor state.