Abstract

This thesis focuses on the experimental creation and detection of different types of quantum correlations using nuclear magnetic resonance (NMR) hardware. The idea of encoding computational problems into physical quantum system and then harnessing the quantum evolution to perform information processing is at the core of quantum computing. Quantum entanglement is a striking feature exhibited by composite quantum systems which has no classical analog. It has been shown that quantum entanglement is a key resource to achieve computational speedup in quantum information processing and for quantum communication related tasks. Creation and detection of such correlations experimentally is a major thrust area in experimental quantum computing. Main goals of the studies undertaken in this thesis were to design experimental strategies to detect the entanglement in a 'state-independent' way and with fewer experimental resources. Experimental schemes have been devised which enables the measurement of desired observable with high accuracy and these schemes were utilized in all the investigations. Experimental protocols were successfully implemented to detect the entanglement of random two-qubit states. Further, the schemes for the experimental detection as well as classification of generic and general three-qubit pure states have also been devised and implemented successfully. Detection of quantum correlations possessed by mixed separable states, bound-entanglement for states of $2 \otimes 4$ systems and non-local nature of quantum systems were also investigated. In all the investigations, results were verified by one or more alternative ways *e.g.* full quantum state tomography, quantum discord, negativity and n-tangle.

Content of the thesis has been distributed in seven chapters and the chapter-wise abstract is as follows.

Chapter 1

This chapter briefly introduces the field of quantum computation followed by the main features of NMR quantum processor architecture. Latter part of the chapter describes the theory of entanglement detection and experimental realization on various hardware. Chapter concludes with goals and motivations for the work undertaken in this thesis.

Chapter 2

This chapter focuses on the entanglement detection of random two-qubit states. Random local measurements have recently been proposed to construct entanglement witnesses and thereby detect the presence of bipartite entanglement. We experimentally demonstrate the efficacy of one such scheme on a two-qubit NMR quantum-information processor. We show that a set of three random local measurements suffices to detect the entanglement of a general two-qubit state. We experimentally generate states with different amounts of entanglement and show that the scheme is able to clearly witness entanglement. We perform complete quantum state tomography for each state and compute state fidelity to validate our results. Further, we extend previous results and perform a simulation using random local measurements to optimally detect bipartite entanglement in a hybrid system of $2 \otimes 3$ dimensionality.

Chapter 3

In this chapter the focus is on a more general kind of quantum correlation possessed by separable states. A bipartite quantum system in a mixed state can exhibit non-classical correlations, which can go beyond quantum entanglement. While quantum discord is the standard measure of quantifying such general quantum correlations, the non-classicality can be determined by simpler means via the measurement of witness operators. We experimentally construct a positive map to witness non-classicality of two-qubits in an NMR system. The map can be decomposed in terms of measurable spin magnetization so that a single run of an experiment on an ensemble of spins suffices to detect the non-classicality in the state, if present. We let the state evolve in time and use the map to detect

non-classicality as a function of time. To evaluate the efficacy of the witness operator as a means to detect non-classicality, quantum discord was measured by performing full quantum state tomography at each time instant and obtain a fairly good match between the two methods.

Chapter 4

This chapter details the experimental detection of the entanglement present in arbitrary three-qubit pure quantum states on an NMR quantum information processor. Measurements of only four observables suffice to experimentally differentiate between the six classes of states which are inequivalent under stochastic local operation and classical communication (SLOCC). The experimental realization is achieved by mapping the desired observables onto Pauli z-operators of a single qubit, which is directly amenable to measurement. The detection scheme is applied to known entangled states as well as to states randomly generated using a generic scheme that can construct all possible three-qubit states. The results are substantiated via direct full quantum state tomography as well as via negativity calculations and the comparison suggests that the protocol is indeed successful in detecting tripartite entanglement without requiring any *a priori* information about the states.

Chapter 5

This chapter details the experimental creation and characterization of a class of qubit-ququart PPT (positive under partial transpose) entangled states using three nuclear spins on an NMR quantum information processor. Entanglement detection and characterization for systems with a Hilbert space dimension $> 2 \otimes 3$ is nontrivial since there are states in such systems which are both PPT as well as entangled. The experimental detection scheme that we employed for the detection of this qubit-ququart PPT entanglement was based on the measurement of three Pauli operators. The class of states considered, in the current study, is an incoherent mixture of five pure states. Measuring three Pauli operators, with high precision using our recently devised method, is crucial to detect entanglement. All the five states were prepared with high fidelities and the resulting PPT entangled states were prepared with mean fidelity ≥ 0.944 using temporal averaging technique.

Chapter 6

This chapter presents the experimental investigations of non-local nature of quantum correlations possessed by multipartite quantum states. It has been shown that fewer body correlations can reveal the non-local nature of the correlations arising from quantum mechanical description of the nature. Such tests on the correlations can be transformed to a semi-definite-program (SDP). This study presents the experimental implementation of Navascués-Pironio-Acín (NPA) hierarchy on NMR hardware utilizing three nuclear spins. The protocol has been tested on two types of genuine tripartite entangled states. In both the cases the experimentally measured correlations were used to formulate the SDP under linear constraints on the entries of the moment matrix. It has been observed that in both the cases SDP failed to find a semi-definite-positive moment matrix consistent with the experimental data which is indeed the signature that the observed correlations can not arise from local measurements on a separable state and hence are non-local in nature. This also confirms that both the states under test are indeed entangled. Results were verified by direct full quantum state tomography in each case.

Chapter 7

This chapter summarizes the results of all the projects constituting this thesis, and the key findings, with possible future directions of work.