EDITORIAL

How to control decoherence and entanglement in quantum complex systems?

Theory and experiment have not fully resolved the *apparent dichotomy*, which has agonized physics for the past eighty years: on the one hand, the description of microsystems by quantum mechanics and, on the other, the description of macrosystems by classical dynamics or statistical mechanics. Derivations of the time-irreversible Liouville equation for an open quantum system, based on projecting out its environment, have narrowed the gap between the quantum and classical descriptions. Yet our 'classical' intuition continues to be confronted by quantum-mechanical results like the Einstein–Podolsky–Rosen paradox that challenges the classical notion of locality, or the quantum Zeno effect which suggests that the isolation of a system is not the only way to preserve its quantum state.

There are two key concepts in any discussion of such issues. The first, which is responsible for the most salient nonclassical properties, is *entanglement*, that is partial or complete correlation or, more generally, inseparability of the elements comprising a *quantum ensemble*. Even after their interaction has ceased, this inseparability, originating from their past interaction, can affect the state of one element when another element is subject to a nonunitary action, such as its measurement, tracing- out, or thermalization. The second key concept is *decoherence* of open quantum systems, which is the consequence of their entanglement with their environment, a 'meter' or a thermal 'reservoir', followed by the tracing-out of the latter. Despite new insights into entanglement and decoherence, there are still no complete, unequivocal answers to the fundamental questions of the transition from quantal to classical behaviour: how do irreversibility and classicality emerge from unitarity as systems and their environments become increasingly *complex*? At what stage does system–meter entanglement give rise to a classical readout of the meter? Is there an upper limit on the size or complexity of systems displaying entanglement?

Major developments have opened new vistas into *controlled entanglement*, which is the resource of quantum information processing. However, these developments have mainly focused on ensembles of simple two- and three-level systems that are thoroughly isolated from their environments. Treatments of coherence in quantum computing have mostly assumed that only a single or a few the elements of the quantum ensemble may simultaneously undergo an uncontrolled intervention—a quantum error. Decoherence-control protocols for more general types of errors are still incomplete.

In order to resolve the outstanding issues of the quantum–classical transition, and study the control of entanglement and decoherence without the foregoing restrictions, we must venture into the domain of *Quantum Complex Systems* (QUACS), either consisting of a large number of inseparable elements or having many coupled degrees of freedom.

Our conviction is that fundamental understanding and manipulation of entanglement within QUACS or their entanglement with the environment or a meter, call for the creation of a new conceptual framework or paradigm, that would encompass phenomena common to cold atoms in laser fields, large molecules, Josephson junctions, quantum gases and solids, with the view of employing these systems for quantum information processing and computing. Progress within this paradigm should allow us to answer the questions: does entanglement play an essential role in the evolution of large collections of complex systems? What are the size and complexity limits of systems and ensembles still controllable by an external intervention? What are the most appropriate decoherence protection schemes and control algorithms?

This special issue addresses the challenge of understanding in depth and manipulating the basic quantum properties of optical, atomic, molecular and condensed-matter QUACS, and large ensembles thereof.

In view of the interdisciplinary character of this issue, we find it expedient to look at the presented articles not only according to the physical objects they describe, but also from a unifying standpoint. Several *unifying themes* may be discerned:

- memory effects in dephasing and relaxation;
- protection of quantum information by its distribution throughout the ensemble;
- control of decoherence and entanglement by time-dependent interventions or measurements;
- manifestations of entanglement in scattering off statistical ensembles;
- measurment-induced dynamics.

The concerted discussion of the topics outlined above should help us advance the new paradigm that addresses our abilities to diagnose and manipulate the entangled states of complex quantum objects and their robustness against decoherence. These abilities are required for quantum information (QI) applications in matter–wave interferometry in molecular, semiconducting or superconducting systems. On the fundamental level, this book may help establish the notion of dynamical *information exchange* between quantum systems and chart in detail the route from unitarity to classicality.

Further developments within the outlined paradigm should yield novel, advantageous QI processing schemes and high-sensitivity interferometers, owing to decoherence suppression and effective control of many degrees of freedom. In the long run, these strategies may prove to be the first step towards the (hitherto unattempted) use of entanglement in nanotechnology, metrology and chemistry, with potentially remarkable novel applications.

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Guest Editors