Macroscopic Schrödinger cat resistant to particle loss and local decoherence

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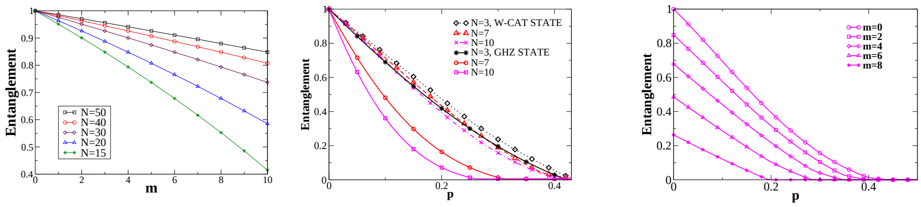
The recent developments in computation and communication tasks have underlined the necessity to preserve quantum coherence in states shared by a large number of quantum systems [1]. Feynman proposed that complex and large quantum systems can be efficiently simulated only by using a quantum computer [2]. Shors algorithm demonstrated that quantum algorithms can be used to efficiently solve problems that may not be possible with classical ones [3]. To build a viable quantum computer that can compile and implement a quantum algorithm, which outperforms the ones running on classical machines, requires quantum coherence preserved in a system of about 1000 qubits [4]. Coherence in quantum states of a large number of particles is one of the essential ingredients for building a quantum communication network [5]. Such exciting developments on the theoretical front were accompanied by several experimental proposals and realizations, by using, e.g., photons, ion traps, cold atoms, and nuclear magnetic resonance.

A macroscopic entangled state was first introduced by Schrödinger in his seminal 1935 paper [6] through the concept of the Schrödinger cat, which is an entangled state between a microscopic system and a macroscopic one. The microscopic system can be an atom, which can decay spontaneously, with the undecayed state $|\text{up}\rangle$ and the decayed state $|\text{down}\rangle$ making up a two-dimensional complex Hilbert space (qubit). The macroscopic system was also conceived as a qubit made up of the alive and dead states of a cat, respectively denoted as $|\text{alive}\rangle$ and $|\text{dead}\rangle$. The quantum state of the combined micro-macro system was considered to be $\frac{1}{\sqrt{2}}(|\text{up}\rangle|\text{alive}\rangle + |\text{down}\rangle|\text{dead}\rangle)$. While such micro-macro superposition have since been found to be significant in technological pursuits, they are also fundamentally important, e.g., for understanding the quantum measurement problem and the quantum-to-classical transition [7, 8].

It is of vital importance to investigate the effects of environmental noise on quantum superpositions of large systems, for understanding their fundamental as well as technological implications. Usually, the environmental effect that is considered for such a state is decoherence. The classic example of micro-macro superposition is the Greenberger-Horne-Zeilinger (GHZ) state [9]. It is well known that the GHZ state loses all quantum coherence if even a single qubit is lost. Here we introduce a new micro-macro superposition state and call it as H_C state [10]. We show that the H_C state is robust, i.e., it can preserve quantum coherence in the form of quantum correlations between its micro and macro sectors, against loss of a finite fraction of its particles (see Fig. 1(a)) and against local depolarizations on all of its particles (see Fig. 1(b)), and with the simultaneous action of both of these noise effects (see Fig. 1(c)).



(a) (b) (c)

Figure 1: (a) Quantum entanglement after particle loss in the H_C state. The horizontal axis represents the number of particles lost (m) from the macroscopic part of the H_C state, while the vertical one represents the entanglement between the micro and the macro parts of the H_C state after particle loss. The entanglement with respect to m is plotted for different initial number of particles, N. (b) Entanglement of GHZ and H_C states against local decoherence. While the discontinuous lines are for the GHZ states, the continuous ones are for the H_C state. The horizontal axis represents the (decohering noise) parameter p, and the vertical axis is the entanglement in the micro:macro bipartition. (c) Effect of local decoherence and particle loss on the H_C state. Entanglement in the micro:macro bipartition is plotted on the vertical axis against the depolarizing parameter (p) and the number of lost particles.

We then compare the robustness of this state with other quantum states of large systems. In particular, we find that for a finite number of particles in the macroscopic part, the H_C state is more robust to local depolarizing noise than the GHZ state. Such investigations can potentially be a step towards building quantum memory devices using large systems.

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