Decoherence scaling transition in the dynamics of quantum information scrambling*

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The characterization and understanding of the complex dynamics of interacting many-body quantum systems is an outstanding problem in physics [1,2]. They play a crucial role in condensed matter physics, cosmology, quantum information processing and nuclear physics [3,4]. A particularly urgent issue is the reliable control of many-body quantum systems, as it is perhaps the most important step towards the development and deployment of quantum technologies [5]. Their control is never perfect and the fragility of quantum states to perturbations increases with the system size [6, 7]. Accordingly, information processing with large quantum systems remains a challenging task. It is therefore of paramount importance to reduce the sensitivity to perturbations, particularly for large systems, to minimize the loss of quantum information. As we show here, achieving this goal may be more realistic than it is currently assumed: we demonstrate that the sensitivity of a quantum system to environmental noise can become qualitatively smaller, if the control operations applied to it surpass a certain threshold.

We use the tools of solid-state Nuclear Magnetic Resonance to assess the sensitivity to perturbations of a controlled quantum dynamics in a many-body system. We report on a series of experimental quantum simulations that allow to quantify the sensitivity of a controlled Hamiltonian evolution to perturbations that drive the system away from the targeted evolution. Based on out-of-time order correlations [3], we demonstrate that the fidelity decay rate of the controlled dynamics –measured with the Loschmidt Echo [8,9]– increases with the instantaneous cluster-size K, as a power law $\propto K^{\alpha}$, with α depending on the perturbation strength. Strikingly, our results evidence two qualitatively different fidelity decay regimes with different scaling laws associated with a sudden change of the exponent α. For perturbations larger than a given threshold, the controlled dynamics is localized, as manifested by a saturation of the cluster-size growth $K(t)$. This therefore imposes a limit on the number of qubits that can be controlled during a quantum operation. However, for perturbations lower than the threshold, the cluster-size K grows indefinitely and the exponent α drops abruptly, making the quantum dynamics of large systems qualitatively more robust against the perturbation. This sudden sensitivity reduction to perturbations is a promising quantum feature that may be used to implement reliable quantum information processing with many-body systems for novel quantum technologies.

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