Non-thermalizing Dynamics in Quantum Many-Body Systems on Complex Interaction Networks

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The implementation of quantum simulators using engineered quantum many-body systems has made it possible to experimentally observe relaxation processes that were previously difficult to access. According to the eigenstate thermalization hypothesis (ETH), isolated quantum many-body systems thermalize generically, with notable exceptions. The most well-known exception is many-body localization (MBL), in which strong disorder prevents thermalization. More recently, a distinct class of non-thermalizing behavior has been identified: many-body scars (MBS) [1,2], wherein a small number of special eigenstates embedded in an otherwise thermal spectrum exhibit anomalously low entanglement and give rise to persistent quantum revivals.

Both MBL and MBS are known to depend sensitively on the symmetry and interaction structure of the system. While extensive theoretical and experimental work has clarified the nature of these non-thermalizing states in lattice systems, their fate in more general interaction topologies remains largely unexplored. In this work, we numerically investigate the relationship between interaction network structure and quantum many-body dynamics, with the goal of identifying conditions for the emergence of MBL and MBS beyond the lattice interaction networks.

We study the transverse-field Ising model defined on randomly generated interaction networks. For each network realization, we perform exact/approximated diagonalization of the Hamiltonian and examine the entanglement/participation entropy of all eigenstates as a diagnostic for non-thermalizing behavior. By systematically varying both the interaction network structure and the pattern of longitudinal fields applied to individual spins, we map out the conditions under which nontrivial eigenstates arise. Consistent with prior work on lattice systems, we find that combinations of interactions and longitudinal fields that result in vanishing local effective fields on individual spins are particularly responsible for the formation of nontrivial eigenstates.

To characterize the resulting dynamics, we identify the Fock state closest to each low-entanglement/low-participation-entropy eigenstate and use it as an initial state for numerical time evolution via the Schrödinger equation. In the majority of cases, the dynamics exhibits signatures consistent with MBL, including suppressed entanglement/participation entropy growth and absence of thermalization. For a subset of eigenstates, we observe behavior reminiscent of MBS, evidenced by periodic revivals in local observables. However, unlike the canonical MBS found in lattice models — which involve coherent oscillations of all spins — the scarring observed here is spatially localized, involving only a subset of spins in the network. This finding suggests that the network topology plays a crucial role in shaping the spatial extent and coherence of many-body scars, and opens new directions for understanding non-thermalizing quantum dynamics in systems with irregular or heterogeneous connectivity.

References:

[1] C. J. Turner, A. A. Michailidis, D. A. Abanin, M. Serbyn, and Z. Papić, Weak ergodicity breaking from quantum many-body scars, Nat. Phys. 14, 745 (2018).

[2] C. J. Turner, A. A. Michailidis, D. A. Abanin, M. Serbyn, and Z. Papić, Quantum scarred eigenstates in a Rydberg atom chain: Entanglement, breakdown of thermalization, and stability to perturbations, Phys. Rev. B 98, 155134 (2018).