Bounding the resources for thermalizing many-body localized systems

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Abstract We study how a finite thermal environment can induce thermalization in a-thermal systems, focusing on the specific setting where the system exhibits many-body localization (MBL). We derive upper and lower bounds on the size of the heat bath required to thermalize a many-body system out of equilibrium, under a broad class of thermodynamic models. These bounds show that the max-relative entropy, under certain conditions on the Hamiltonian, characterizes the robustness of MBL systems against thermalization. We apply our results to the disordered Heisenberg chain, and numerically study the robustness of its MBL phase in terms of the required bath size.

Keywords Quantum Thermodynamics, Quantum Resource Theories, Many-Body Localization

When pushed out of equilibrium, closed interacting quantum many-body systems generically relax to an equilibrium state that can be described using thermal ensembles [1–3]. However, some systems equilibrate to a non-thermal state and exhibit features of what is known as *many-body localization* (MBL) [4, 5]. Whether the MBL phase is stable when the system is coupled to an external environment is an open question which has been recently considered in several papers [6–9]. This question is of critical importance for the experimental realization of many-body localized systems, and for its fundamental implications on the process of thermalization in quantum systems.

We study the robustness of the MBL phase under external dissipative processes. More precisely, we consider a many-body localized system coupled to a thermal reservoir with a finite size. The coupling is described by a broad class of physically-relevant interaction models, where the interactions between system and environment are described in terms of stochastic collisions which preserve the energy of the global system. The bath is chosen to be composed by many independent copies of the thermal state we expect the system to equilibrate into, an assumption satisfied in some experimental setups [10–12] where copies of one-dimensional spin lattices are allowed to interact with each other.

The main tools we employ for deriving our bounds are taken from the field of quantum information theory. Specifically, we make use of a technical result known as *convex split lemma* [13, 14], first used in the context of quantum Shannon theory and decoupling tasks. We connect this mathematical result to the above class of thermodynamic models, that can be used to describe thermalization processes in quantum systems [15]. Furthermore, we show that under certain assumptions on the system Hamiltonian, no process within this class can bring the system closer to thermal equilibrium than the one associated with the convex split lemma.

With the help of the above results, we derive lower and upper bounds to the size of the external bath needed to thermalize a system. These bounds depend on the max-relative entropy [16], an element in the family of quantum Rényi divergences [17], and on its smoothed version. In order to illustrate the practical relevance of our results, we numerically compute these bounds for a specific system exhibiting many-body localization, namely the disordered Heisenberg chain. Our findings suggest that the MBL phase is robust to thermalization despite being coupled to an external bath, under our broad class of collision models. Furthermore, our results extend the characterization of the stability of MBL systems to scenarios where the external environment has a finite size and can be strongly coupled to the system.

References

[1] J. M. Deutsch, "Quantum statistical mechanics in a closed system," *Physical Review A*, vol. 43, no. 4, p. 2046, 1991.

[2] M. Srednicki, "Chaos and quantum thermalization," *Physical Review E*, vol. 50, no. 2, p. 888, 1994.

[3] S. Popescu, A. J. Short, and A. Winter, "Entanglement and the foundations of statistical mechanics," *Nature Physics*, vol. 2, pp. 754–758, 2006.

[4] V. Oganesyan and D. A. Huse, "Localization of interacting fermions at high temperature," *Phys. Rev. B*, vol. 75, p. 155111, 2007.

[5] M. Schreiber, S. S. Hodgman, P. Bordia, H. P. Lüschen, M. H. Fischer, R. Vosk, E. Altman, U. Schneider, and I. Bloch, "Observation of many-body localization of interacting fermions in a quasi-random optical lattice," *Science*, vol. 349, p. 842, 2015.

[6] M. H. Fischer, M. Maksymenko, and E. Altman, "Dynamics of a Many-Body-Localized System Coupled to a Bath," *Physical Review Letters*, vol. 116, p. 160401, Apr. 2016.

[7] R. Nandkishore, S. Gopalakrishnan, and D. A. Huse, "Spectral features of a many-body-localized system weakly coupled to a bath," *Physical Review B*, vol. 90, p. 064203, Aug. 2014.

[8] E. Levi, M. Heyl, I. Lesanovsky, and J. P. Garrahan, "Robustness of Many-Body Localization in the Presence of Dissipation," *Physical Review Letters*, vol. 116, p. 237203, June 2016.

[9] S. Johri, R. Nandkishore, and R. Bhatt, "Many-Body Localization in Imperfectly Isolated Quantum Systems," *Physical Review Letters*, vol. 114, p. 117401, Mar. 2015.

[10] P. Bordia, H. P. Lüschen, S. S. Hodgman, M. Schreiber, I. Bloch, and U. Schneider, "Coupling identical one-dimensional many-body localized systems," *Phys. Rev. Lett.*, vol. 116, p. 140401, Apr 2016.

[11] P. Bordia, H. Lüschen, S. Scherg, S. Gopalakrishnan, M. Knap, U. Schneider, and I. Bloch, "Probing slow relaxation and many-body localization in two-dimensional quasiperiodic systems," *Physical Review X*, vol. 7, no. 4, p. 041047, 2017.

[12] A. Rubio-Abadal, J.-y. Choi, S. Zeiher, J. Hollerith, J. Rui, I. Bloch, and C. Gross, "Many-body delocalization in the presence of a quantum bath," *arXiv*, 2018.

[13] A. Anshu, V. K. Devabathini, and R. Jain, "Quantum Communication Using Coherent Rejection Sampling," *Physical Review Letters*, vol. 119, no. 12, p. 120506, 2017.

[14] A. Anshu, M.-H. Hsieh, and R. Jain, "Quantifying Resources in General Resource Theory with Catalysts," *Physical Review Letters*, vol. 121, p. 190504, Nov. 2018.

[15] L. Diósi, T. Feldmann, and R. Kosloff, "On the exact identity between thermodynamic and informatic entropies in a unitary model of friction," *International Journal of Quantum Information*, vol. 4, no. 01, pp. 99–104, 2006.

[16] N. Datta, "Min- and Max-Relative Entropies and a New Entanglement Monotone," *IEEE Transactions on Information Theory*, vol. 55, pp. 2816–2826, June 2009.

[17] M. Müller-Lennert, F. Dupuis, O. Szehr, S. Fehr, and M. Tomamichel, "On quantum rényi entropies: A new generalization and some properties," *Journal of Mathematical Physics*, vol. 54, no. 12, p. 122203, 2013.