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Symmetry shapes thermodynamics of macroscopic quantum systems

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Symmetries play a fundamental role in shaping physical theories, from quantum mechanics to thermodynamics. Studying the entropic, energetic, or dynamic signatures of underlying symmetries in quantum systems is an active field of research, from fundamental questions about entropy scalings, ground state properties, or thermalization, to the optimization of quantum computing or numerical simulation procedures, and is gaining momentum due to rapid experimental advances, particularly in cold atoms [1].

In this work [2], we derive a systematic approach to the thermodynamics of quantum systems based on the underlying symmetry groups. We show that the entropy of a system can be described in terms of group-theoretical quantities that are largely independent of the details of its density matrix.
We apply our technique to generic N identical interacting d-level quantum systems. Using permutation invariance, we find that, for large N, the entropy displays a universal large deviation behavior with a rate function s(x) that is completely independent of the microscopic details of the model, but depends only on the size of the irreducible representations of the permutation group.
In turn, the partition function is shown to satisfy a large deviation principle with a free energy $f(x)=e(x)-s(x)/\beta$, where e(x) is a rate function that only depends on the ground state energy of particular subspaces determined by group representation theory.
We demonstrate the power of our approach by applying it to the nontrivial task of describing phase transitions governed by the interplay of quantum and thermal fluctuations in the transverse-field Curie-Weiss model.

[1] Masahito Ueda. "Quantum equilibration, thermalization and prethermalization in ultracold atoms."Nat. Rev. Phys., 2(12):669, 2020.

[2] Vasco Cavina, Ariane Soret, Timur Aslyamov, Krzysztof Ptaszyński, and Massimiliano Esposito. "Symmetry shapes thermodynamics of macroscopic quantum systems". arXiv:2402.04214, 2024.

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