WORK EXTRACTION VIA LOCAL GATES AND PHASE TRANSITIONS IN OPEN QUANTUM SYSTEMS

Grazia Di Bello[1,*], Vittorio Cataudella[2,3], Giulio De Filippis[2,3], Donato Farina[4], Francesco Formicola[4], David Jansen[5], Carmine Antonio Perroni[2,3]

[1]Dip. di Fisica E. Pancini - Università di Napoli Federico II - I-80126 Napoli, Italy, https://orcid.org/0000-0001-9838-6631
[2]SPIN-CNR and Dip. di Fisica E. Pancini - Università di Napoli Federico II - I-80126 Napoli, Italy
[3]INFN, Sezione di Napoli - Complesso Universitario di Monte S. Angelo - I-80126 Napoli, Italy
[4]Dip. di Fisica E. Pancini - Università di Napoli Federico II - I-80126 Napoli, Italy, ORCID
[5]ICFO-Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology, 08860 Castelldefels (Barcelona), Spain
*grazia.dibello@unina.it

ABSTRACT

We investigate the dynamical and thermodynamic properties of an open two-qubit Rabi model [1; 2] and a disordered XXZ Heisenberg spin chain using advanced numerical methods, including the density-matrix renormalization group (DMRG) and time-dependent variational principle (TDVP). These techniques describe open quantum systems states as matrix product states (MPSs). Our focus is on work extraction from a subsystem treated as an open quantum battery, particularly its relation to quantum phase transitions. We analyze ergotropy, the maximum extractable work, in the context of many-body phenomena such as quantum phase transitions. Local ergotropy [3], which quantifies work extraction in an uncontrollable environment, is studied across a Berezinskii-Kosterlitz-Thouless phase transition in the Rabi model, compared with its "switch-off" counterpart, where the energy cost of decoupling the subsystem from the environment is included in the work calculation. We propose a protocol for charging, storage, and work extraction optimized via Bayesian methods [4], revealing that strong system-bath coupling nearly doubles local ergotropy. Furthermore, ergotropy fluctuations serve as signatures of equilibrium quantum phase transitions (see Fig. 1).

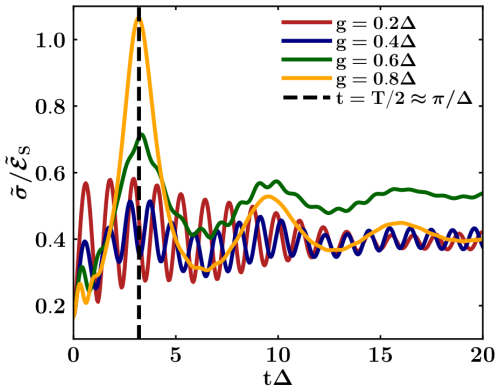

Figure 1: Relative fluctuations of the lower bound of local ergotropy (solid lines) as a function of dimensionless time for increasing system-environment coupling g/Δ (from red to orange). The vertical dashed black line is the time when the bath is in counterphase, farthest from initial state.

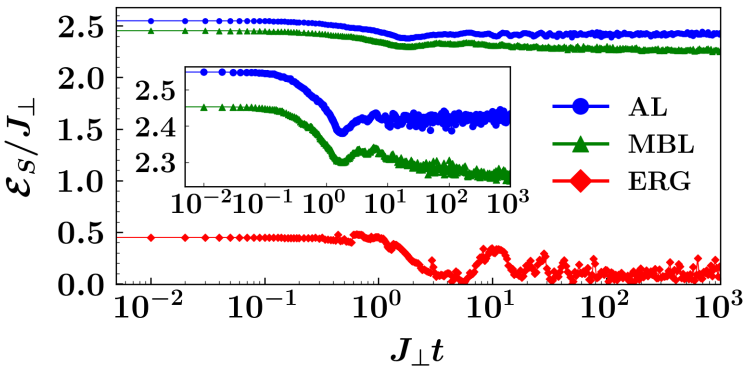

Figure 2: Local ergotropy as a function of dimensionless time for AL (blue circles), MBL (green triangles) and ergodic (red diamonds) phases. The inset provides a zoomed-in view of the local ergotropy as a function of time for the two localized phases.

Extending this framework, we examine the disordered XXZ Heisenberg spin chain, where the first two spins function as a quantum battery coupled to a spin bath [5]. Using the Néel state as an initial condition, we compute ergotropic quantities to identify transitions between many-body localized (MBL), Anderson localized (AL), and ergodic phases. Long-time behavior varies across these phases, with AL exhibiting saturation, MBL showing logarithmic decay, and the ergodic phase experiencing rapid decay of extractable work (see Fig. 2). Our results demonstrate that ergotropic quantities witness MBL-AL-ergodic transitions and that localized quantum batteries discharge more slowly and store more work, offering a pathway for experimental validation using two-qubit operations and energy measurements.

Keywords: Open quantum systems, Quantum batteries, Ergotropy, Quantum phase transitions, Many-body localization.

Physics and Astronomy Classification Scheme: 05.30.Rt (Quantum phase transitions), 03.65.Yz (Decoherence in quantum mechanics), 75.10.Pq (Spin chain models).

REFERENCES

[1] G. De Filippis, A. de Candia, G. Di Bello, C. A. Perroni, L. M. Cangemi, A. Nocera, M. Sassetti, R. Fazio, and V. Cataudella, *Signatures of Dissipation Driven Quantum Phase Transition in Rabi Model*, Phys. Rev. Lett. **130** (2023), 210404.

[2] G. Di Bello, A. Ponticelli, F. Pavan, V. Cataudella, G. De Filippis, A. de Candia, and C. A. Perroni, *Environment induced dynamical quantum phase transitions in two-qubit Rabi model*, Commun. Phys. **7** (2024), 364.

[3] R. Salvia, G. De Palma, and V. Giovannetti, *Optimal local work extraction from bipartite quantum systems in the presence of Hamiltonian couplings*, Phys. Rev. A **107** (2023), 012405.

[4] G. Di Bello, D. Farina, D. Jansen, C. A. Perroni, V. Cataudella, and G. De Filippis, *Local Ergotropy and its fluctuations across a dissipative quantum phase transition*, Quantum Sci. Technol. **10** (2024), 015049.

[5] F. Formicola, G. Di Bello, G. De Filippis, V. Cataudella, and C. A. Perroni, *Local ergotropy dynamically witnesses many-body localized phases*, arXiv:2502.20002 (2025).