Work extraction via local gates and phase transitions in open quantum systems

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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. Specifically, we employ the density-matrix renormalization group (DMRG) algorithm for equilibrium conditions and the time-dependent variational principle (TDVP) for out-of-equilibrium scenarios. These methods are applied to describe the states of complex open quantum systems, represented as matrix product states (MPSs), a 1D variational tensor network ansatz. Our study focuses on work extraction from a subsystem treated as an open quantum battery, with particular attention to its relationship with quantum phase transitions. Ergotropy, which quantifies the maximum extractable work from a quantum system, is examined in the context of many-body phenomena such as quantum phase transitions. We also explore the concept of local ergotropy [3], which measures the ability to extract work in an uncontrollable environment compared to its "switch-off" counterpart, where the energy cost of decoupling the subsystem from the environment is included in the work calculation.

In the two-qubit Rabi model, we investigate local ergotropy and its fluctuations across the Berezinskii-Kosterlitz-Thouless quantum phase transition using DMRG and TDVP methods. We propose a realistic protocol for charging, quasi-decoherence-free storage, and work extraction, employing a Bayesian optimization algorithm to determine the optimal local unitary gate sequence for maximum work extraction [4]. Our findings reveal that strong coupling to an external bath nearly doubles local ergotropy after charging, due to subsystem-bath interactions. Additionally, local ergotropy and its fluctuations can witness equilibrium quantum phase transitions. (see Fig. 1 (a)).

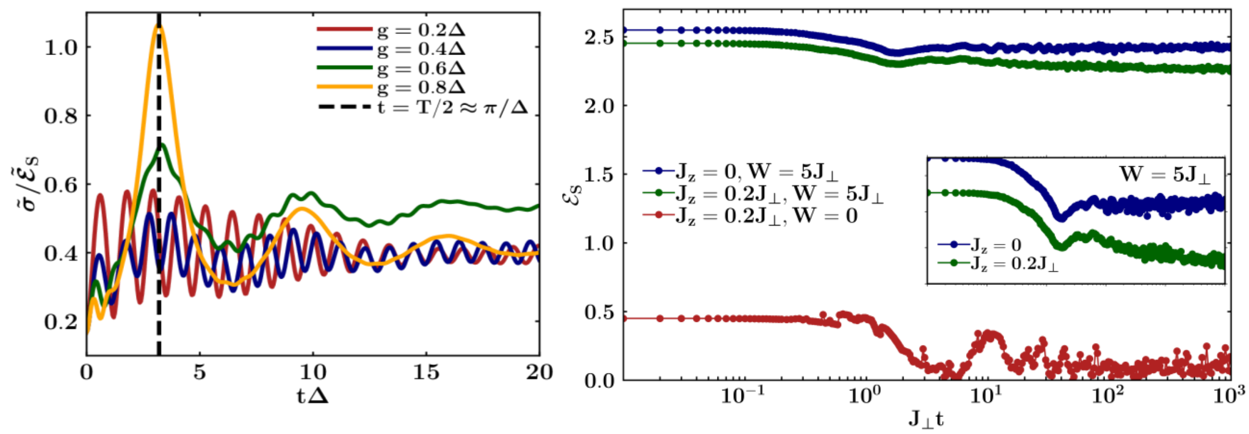

Fig. 1. (a) Relative fluctuations of the lower bound of the local ergotropy (solid lines) as a function of dimensionless time for increasing g/Δ (from red to orange). The vertical dashed black line represents the time when the bath is in counterphase, farthest from the initial state. (b) Local ergotropy as a function of dimensionless time for AL (blue dots), MBL (green dots) and ergodic (red dots) phases.

Extending this framework to many-body systems, we analyze the disordered XXZ Heisenberg spin chain, where the first two spins act as an open quantum battery and the rest of the chain serves as the "bath" [5]. Using the Néel state as the initial condition, we compute local and switch-off ergotropies to study the transition from the many-body localized (MBL) phase to Anderson localization (AL) and ergodic phases. We observe long-times saturation of ergotropic quantities in the AL phase, logarithmic decay in the MBL phase, and rapid decay to zero in the ergodic phase (see Fig. 1 (b)). We demonstrate that ergotropic quantities witness MBL-AL-ergodic transitions and can be experimentally probed only requiring two-qubit gate operations and energy measurements. Our results also show that localized quantum batteries discharge more slowly than ergodic ones and store greater amounts of work.

References:

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