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Energy Extraction from Unknown Quantum States and Universal Ergotropy Bounds

Ergotropy, the maximum extractable work via unitary operations, is a fundamental measure of the energetic content of a quantum system. However, its evaluation and the corresponding energy-extraction protocol typically require precise knowledge of the system's state. In this work, we investigate the minimum energy that can be extracted with a unitary protocol that is independent from any knowledge of the state but its average energy. We find the optimal unitary protocol to extract such minimum energy from any finite-dimensional Hamiltonian. Remarkably, we observe that such unitary protocol is the same for every finite-dimensional Hamiltonian.

We show that when the mean energy exceeds a threshold value, given by the arithmetic mean of the energy eigenvalues, anti-passive states are the states of minimum extractable energy, and the unitary protocol to extract energy from them guarantees to extract at least the same amount of energy from every other state. Depending on the Hamiltonian spectrum, we determine the minimum energy extracted either analytically or through an exact algorithm in a number of steps quadratic in the dimension of the system. A key implication of our findings is that no unitary protocol can guarantee to extract coherent ergotropy from an unknown quantum state. Finally, we discuss a potential experimental implementation based on a system interacting with a harmonic oscillator via a Tavis-Cummings coupling, a setup that is feasible in solid-state architectures.

Theme

Theme 3. Theoretical and experimental methods for quantum effects in energy processes

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