Measure-invariant parameter paths for ergotropic advantage in many-body systems

Alhun Aydin[1,2]

[1]Sabanci University, Istanbul, Turkey, [2]Harvard University, Cambridge, USA

Spectral gap engineering in many-body systems is a challenging task in quantum thermodynamics since most controls impose global spectral shifts with unavoidable energetic costs. Size-invariant shape transformations (SIST), shaping the boundaries of a confined domain by preserving its Lebesgue measure, have been shown to keep the Weyl density of states fixed while inducing nonuniform level scaling and unusual thermodynamic responses, such as spontaneous transitions into lower-entropy configurations [1, 2, 3]. Here we generalize SIST beyond geometry by introducing measure-invariant spectral transformations (MIST): parameter-space paths along which coarse spectral scale is preserved while the spectrum (gaps and eigenvectors) is reshaped. Using an operator–coefficient decomposition, we construct parameter paths that fix low-order spectral moments, enabling selective modification of low-energy gaps and matrix elements. We implement these ideas in the Bose–Hubbard trimer and show that sector-resolved MIST controls produce sizable and tunable changes in low-lying gaps without a global spectral shift. MIST reproduces and extends SIST phenomenology of energy- and entropy-driven spontaneity under quasistatic parameter change. Beyond equilibrium signatures, we demonstrate a genuinely quantum advantage in nonequilibrium thermodynamics: starting from a Gibbs state, MIST quenches convert injected work into ergotropy far more efficiently than conventional affine sweeps of hopping, onsite energies, or interactions. MIST suppresses the injected work associated with the component of the quench that commutes with the initial Hamiltonian, while amplifying the non-passive contribution arising from the non-commuting component responsible for eigenbasis mismatch. This enables a practical route to cost-efficient spectral engineering for quantum thermodynamic tasks such as work extraction, charging, and gap targeting in controllable many-body systems.

References:

[1] A. Aydin, "Spectral properties of size-invariant shape transformation", Phys. Rev. E, 107, 054108, (2023).

[2] A. Aydin and A. Sisman, "Origin of the quantum shape effect", Phys. Rev. E, 108, 024105, (2023).

[3] A. Aydin, "Geometry-induced asymmetric level coupling", Phys. Rev. E, 112, 014121, (2025)