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Maximal steady-state entanglement in autonomous quantum thermal machines

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It is well-known that failure to isolate a quantum system leads to its decoherence. However, quantum thermal machines offer an interesting perspective on this common wisdom. These are systems that explicitly use spontaneous interactions with the environment to perform a task. For these quantum systems, the environment is not detrimental but a resource. A basic conceptual question is therefore whether an autonomous quantum thermal machine, which uses no source of work, external driving or time-coherent control, can generate the strong forms of quantum correlations exclusively from spontaneous interactions with classical reservoirs. It was shown in an earlier work [1] that such a machine actually can generate entanglement between two qubits, only by leveraging a temperature bias. While the entanglement was both weak and noisy, it motivated the following natural question: how strong entanglement is actually possible to produce with these thermodynamically minimalistic resources? In the years since, a series of works have step by step strengthened the entanglement –sometimes at the price of introducing some extra resources. Still, the best entanglement so far obtained is far from optimal. In our work [2], we conclusively solve this problem. We propose a quantum thermal machine which only uses a chemical potential bias in order to generate a maximally entangled qubit pair, or in fact, any desired pure two-qubit entangled state, emerging as a dark state of the system. The key insight is the addition of an extra qubit which serves as an aid for generating the entanglement between other constituents of the machine. The three qubit architecture resembles a generalised coherent population trapping setup from atomic physics. Crucially, we prove that this is the minimal thermal machine that can produce maximal entanglement. Going beyond bipartite entanglement, we generalise our thermal machine to produce genuinely multipartite entangled states of n qubits using an architecture of 2n-1 qubits. Remarkably, the architecture is able to produce W states of an arbitrary number of qubits using only local pairwise interactions and a chemical potential bias. Our results reveal the striking fundamental capabilities of autonomous quantum evolution. [1] New J. Phys. 17, 113029 (2015). [2] arXiv:2401.01776 (2024)

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