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Quantum enhancement of precision in photonic energy harvesters

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We investigate quantum energy harvesters—systems designed to convert an external quantum source, such as an electromagnetic potential, into useful work, in the form of a measurable electric current. The latter can be utilized to power thermal machines or stored in a quantum battery. Our study focuses on multimode continuous-variable (CV) quantum systems, which provide a natural framework for describing and manipulating energy fluctuations at the quantum scale.

A key challenge in energy harvesting is optimizing the precision of work extraction. We show that this depends on the interplay between quantum coherence, entanglement, and non-Gaussianity. To prove it, we establish a hierarchy of analytical upper bounds on the signal-to-noise ratio (SNR) of the harvested energy. These bounds provide fundamental insights into how quantum resources enhance energy transfer. Our results reveal that when the external energy source exhibits nonclassical properties, significant improvements in precision can be achieved. Moreover, if the source is also non-Gaussian, entanglement can be leveraged to further optimize the SNR, leading to near-optimal work extraction.

We demonstrate that entangled multimode states can be engineered to maximize energy harvesting efficiency, finding the optimal parameters that enhance the precision of energy conversion. This suggests that non-Gaussian quantum correlations serve as a resource not only for quantum computation and communication but also for energy processing. By exploiting these quantum effects, we establish a deeper link between the flow of energy and information in quantum systems.

Our theoretical framework can be experimentally realized with current photonic technologies, making it feasible for near-term implementations in quantum laboratories. The ability to precisely control quantum energy transfer is particularly relevant for emerging nanotechnologies, where energy fluctuations at the quantum level start to play a crucial role. Moreover, our findings open new avenues for precision charging in quantum batteries, ensuring that energy is delivered with minimal loss and maximum efficiency.

This work highlights the potential of quantum energy harvesters as a novel platform for energy-efficient quantum technologies. By bridging concepts from quantum thermodynamics, quantum optics, and information theory, we provide a blueprint for designing energy-harvesting systems that harness uniquely quantum advantages. Future research will explore how these principles extend to more complex networked systems and investigate their integration with quantum computing architectures.

Our findings suggest that quantum-enhanced energy processing could revolutionize the way energy is distributed and utilized at the nanoscale, paving the way for next-generation sustainable power solutions in quantum technologies.

Theme

Theme 1. Energy advantage and cost of quantum technology

Primary author: CENTRONE, Federico (ICFO, UBA)

Co-author: POLO, Beatriz (ICFO)

Presenter: CENTRONE, Federico (ICFO, UBA)

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