Scientists propose new scheme for the quantum battery using waveguides

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A lossless and coherent energy exchange between the separated quantum battery and quantum charger is mediated by the electromagnetic field. It permits the realization of a remote-charging and anti-aging quantum battery. Credit: Prof. Jun-Hong An.

A new study by researchers at Lanzhou University and Hubei University proposes a quantum battery (QB) charging scheme based on a rectangular hollow metal waveguide. This approach allows them to overcome environment-induced decoherence and charging distance limitations. The findings are published in *Physical Review Letters*.

The demand and supply for batteries continue to grow with a focus on enhancing energy storage, longevity, and charging capabilities. On this front, scientists are now developing quantum batteries that leverage principles of quantum mechanics to store and supply energy.

The aim is to use fundamental principles of quantum mechanics such as entanglement and coherence to overcome the constraints of classical physics, thereby achieving stronger charging power, higher charging capacity, and larger work extraction compared to classical counterparts.

The new study explores the QB by placing the battery and charger in a rectangular hollow waveguide. This method aims to mitigate the effects of decoherence to achieve long-lasting and efficient QB performance.

Speaking of the team's motivation to explore quantum batteries, the lead author of the study, Prof. Jun-Hong An from Lanzhou University, China, told Phys.org, "Decoherence challenges cause the spontaneous energy loss of QB, which is called the aging of QB."

"The other challenge for the practical performance of QB is its low charging efficiency resulting from the fragility of coherent interactions between the QB and its charger. We wanted to overcome these challenges."

Quantum battery and waveguides

The QB model is based on two two-level systems (TLSs), which are systems having two distinct energy levels. These energy levels are typically represented as a ground state and an excited state.

One system is the battery itself and the other is the charger. The charging and energy exchange processes between these TLSs play a key role in the functioning of the QB system. TLSs are charged by establishing a coherent coupling with other TLSs or external fields.

In the context of QBs, coherent coupling is a synchronized and correlated interaction between these quantum systems, allowing for the transfer or exchange of energy. These coherent interactions are fragile and introduce decoherence into these systems.

"Any quantum system cannot be absolutely isolated from its outer environment, which inevitably induces unwanted decoherence to the system," explained Prof. Jun-Hong.

These models realize charging via direct charger-QB interaction. However, this relationship is affected by the distance between the two resulting in a decline in charging efficiency. To overcome this and the decoherence problem the researchers introduced rectangular hollow waveguides.

A waveguide is a structure that guides waves, typically electromagnetic waves, along a specific path. It acts as a conduit for the waves, confining and directing them to travel in a controlled manner.

"The rectangular hollow metal waveguide is used to collect and guide the electromagnetic field to mediate the energy transfer between the QB and charger," said Prof Jun-Hong.

The energy transfer itself occurs without direct contact between the two TLSs, introducing a novel approach to the QB charging process.

Quantized interactions

The researchers' model hinges on the quantized interaction between the electromagnetic field and matter within a waveguide.

Within the confines of the waveguide, the electromagnetic field possesses specific dispersion relations and bandgap structures, which are parameters influencing its propagation and interactions within the quantum system.

Initially, this electromagnetic field is in a vacuum state, meaning there are no photons in its modes. Meanwhile, the QB is in its ground state, and the charger is in an excited state.

The charger undergoes a transition from an excited state to the ground state, emitting a photon in the electromagnetic field. This introduces an excitation in the electromagnetic field leading to the field having infinite modes (or possible configurations).

The photon subsequently gets absorbed by the QB which transitions to an excited state.

Although having infinite modes in the electromagnetic field would typically induce decoherence in the quantum system, the surprising aspect is that the researchers found this infinite-mode field acts as an environment and, contrary to expectations, facilitates coherent QB-charger energy exchange.

"Our work reveals a mechanism for making a coherent QB-charger energy exchange happen by the mediation role of the infinite-mode electromagnetic field," explained Prof. Jun-Hong.

Charging dynamics and future work

The unexpected finding that decoherence in the system doesn't lead to the aging of the QB contradicts popular belief. Instead, the researchers note that the energy exchange is an optimal charging process—typically expected in scenarios where the charger and QB directly interact.

Further, their QB scheme showed a long range for wireless charging, with the formation of two bound states in the energy spectrum of the total systems (QB-charger-environment) playing a crucial role.

"A take-home message of our work is that the quantum interconnects favored by the waveguide supply us with a useful way to overcome the challenges in the practical realization of QB," added Prof. Jun-Hong.

This improves the effectiveness of QB and opens the door to the possibility of lighter and thinner devices with greater facilitation, which also stands out for its durability.

Prof. Jun-Hong also highlighted that their device was completely safe and harmless as the electromagnetic field is always confined within the waveguide and the QB's energy storage, free from electrochemical reactions, promotes infinite reusability without environmental pollution.

The next step for the researchers is to scale their QB scheme.

"More specifically, we plan to develop a many-body QB model working in the way of remote wireless charging. This could permit us to efficiently incorporate the superiority of quantum entanglement in enhancing the charging power, charging capacity, and the extractable work of a remote-charging and anti-aging QB," concluded Prof. Jun-Hong.

More information: Wan-Lu Song et al, Remote Charging and Degradation Suppression for the Quantum Battery, *Physical Review Letters* (2024). DOI: 10.1103/PhysRevLett.132.090401. On *arXiv*: DOI:

10.48550/arxiv.2308.13784