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Quantum Energy Teleportation without Classical Communication

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ABSTRACT

Quantum energy teleportation (QET) is a protocol that unlocks the extraction of local energy and has been thought to fundamentally require classical communication (CC), since Bob must normally learn Alice's measurement outcome to perform the proper conditional operation (CO). In this work, we demonstrate that CC itself can be removed for the purpose of QET: When Bob's local operation is implemented through a weak coupling to an auxiliary qubit, the interaction naturally adapts to Alice's post-measurement state, thereby realizing the necessary CO without any classical message. This establishes a CC-free form of QET, which broadens its conceptual scope and suggests practical applications such as indirect external control for charging of quantum batteries.

Keywords

Quantum energy teleportation, classical communication, rotating wave approximation, conditional operation

1 INTRODUCTION

Quantum state teleportation (QST) is a well-recognized protocol in quantum information science, enabling the transfer of an arbitrary quantum state between spatially separated parties [BBC+93, BPM+97, FSB+98]. Its validity has been extensively demonstrated through numerous experimental implementations [UJA+04, JRY+10, MHS+12, RXY+17]. The protocol requires a shared pair of entangled qubits between the sender (Alice) and the receiver (Bob), as well as a classical communication channel for transmitting two classical bits. Thus, QST intrinsically relies on both quantum entanglement and classical communication. Importantly, it is well understood that the physical energy associated with the teleported state is not transmitted from Alice. Instead, it is supplied locally by Bob during the state reconstruction process.

In parallel, Hotta introduced quantum energy teleportation (QET), a protocol that enables local energy transfer [Hot09a, Hot11]. First proposed in spin-chain systems [Hot08a], QET has since been generalized to various settings, ranging from relativistic quantum field theory and black-hole physics to trapped ions, harmonic oscillators, and topological phases [Hot08b, Hot10a, Hot09b, Hot10c, Ike23b]. Its relevance to condensed matter and quantum information science has also been explored, including connections to quantum Hall systems, squeezed states, and Gibbs spin models [YIH11, HMY14, FGH13, TH15, IL24]. On the experimental side, initial demonstrations have been reported in NMR platforms and superconducting circuits [RBKMML23, Ike23a, XSK24]. Recent developments highlight long-range QET protocols enabled by combining QST with QET [Ike23c], trade-off relations between the two schemes [WY24], and links to quantum steering [FWW+24].

At first glance, one might be tempted to interpret QET as a protocol for transferring energy between distant locations, analogous to how QST transfers quantum states [Hot09a, Hot11]. Such an interpretation, however, could be misleading and potentially problematic, as it appears to conflict with relativistic causality. A more careful analysis reveals that QET does not directly teleport energy. Instead, what restricts local energy extraction is the principle of strong local passivity (SLP) [FFH14, ASRB+19]. QET acts as a protocol to overcome SLP: it does not transmit energy itself, but rather leverages classical communication to unlock local en-

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ergy from systems that would otherwise remain energetically passive [RBKMML23].

In its original formulation, QET was argued to require four elements: (i) ground-state preparation, (ii) shared entanglement, (iii) Alice's measurement operators commuting with the interaction Hamiltonian, and (iv) classical communication. These conditions, once proposed, have since been widely adopted in subsequent studies. However, from the perspective of SLP, the first three conditions should be regarded as sufficient but not necessary for a system to exhibit SLP and thereby necessitate the use of QET. Recent work has shown that SLP can be present even in the absence of these conditions [XSK25]. This suggests that the traditional requirements can be relaxed, thereby enabling a broader conceptual framework for discussions and practical implementations of QET.

Despite these relaxations, the fourth requirement of classical communication (CC) still remains: Bob must receive information from Alice in order to perform the proper conditional operation (CO) that breaks his local SLP. At first glance, it seems unavoidable that CO necessarily implies CC.

However, relying on CC can introduce several drawbacks. From a security standpoint, the classical channel is vulnerable to interception, allowing an eavesdropper to obtain Alice's measurement outcomes. From a physical standpoint, CC is constrained by the speed of light, which limits the rate at which the protocol can be executed over long distances, thus restricting efficiency. At the microscopic scale, implementing CC can be challenging, since both Alice and Bob may themselves be microscopic quantum systems. Furthermore, transmitting classical signals carries an energy cost, which can render CC impractical in resource-limited environments.

These considerations motivate the question: Can the requirement of CC be eliminated while retaining CO? If so, all four traditional QET requirements would effectively be eliminated.

At first glance, eliminating CC may appear impractical, as it seems to risk violating relativistic constraints. However, our recent investigations indicate that a positive answer is possible, which we now explain.

2 REVIEW ON THE MINIMAL MODEL OF QET

To begin, we briefly review the original minimal model of QET introduced in [Hot10b], which involves two qubits, A and B, shared between two distant parties, Alice and Bob. The Hamiltonian is

$$H_{AB} = -hZ_A - hZ_B + 2\kappa X_A \otimes X_B, \tag{1}$$

where h and κ are positive constants, and X_i and Z_i (with $i \in \{A, B\}$) denote the Pauli operators for qubit i. The two qubits are initially prepared in the ground state $|g\rangle$ of H_{AB}, given by

$$|g\rangle = \cos(\theta)|00\rangle_{AB} - \sin(\theta)|11\rangle_{AB}, \tag{2}$$

with $\tan(2\theta) \equiv \kappa/h$. Since the ground state has the lowest possible energy, neither Alice nor Bob can locally extract the energy from $|g\rangle$.

To enable energy extraction, the QET protocol requires Alice to perform a local measurement using the operators $\{|+\rangle\langle+|, |-\rangle\langle-|\}$, where $|\pm\rangle = (|0\rangle \pm |1\rangle)/\sqrt{2}$. Alice's measurement disturbs the ground state $|g\rangle$, thus injecting energy into the system. Because her measurement operators commute with the interaction Hamiltonian, the injected energy remains localized at Alice's site, only raising the expectation value $\langle -hZ_A \rangle$. One can verify that Bob, by any local general operation (which can be characterized by a general set of Kraus operators) alone, cannot reduce the expectation value $\langle H_{AB} \rangle$, which means that his local energy extraction is forbidden.

For Bob to extract energy, Alice must send her measurement result ($+$ or $-$) via classical communication. Based on this information, Bob applies the CO:

$$G_\pm \equiv \exp[\pm i(\phi - \theta)Y], \tag{3}$$

where $\tan(2\phi) \equiv 2\kappa/h$ and Y is the Pauli-Y operator. One can show that, this CO reduces the expectation value $\langle H_{AB} \rangle$, indicating that Bob has successfully extracted energy locally with the help of CC.

At first glance, the sequence of steps suggests the following interpretation: the system begins in the ground state with no available energy, Alice injects energy on her side, and after transmitting classical information, Bob extracts energy on his side. Importantly, the entire process can be executed on a time scale limited only by the speed of classical communication, which is much faster than the intrinsic dynamics of H_{AB}. As a result, energy cannot naturally propagate from Alice to Bob during this interval. Consequently, the protocol appears to mimic the teleportation of energy between distant parties, with the classical channel enforcing causality by restricting the transfer speed to that of light. Such reasoning seems to justify the protocol's name: "quantum energy teleportation."

However, a closer inspection shows that this interpretation is misleading. Bob's local operations commute with Alice's local Hamiltonian term, $H_A = -hZ_A$, so Alice's injected energy, $\langle H_A \rangle$, remains unaffected by Bob's actions. This implies that the energy Bob extracts does not originate from Alice. Instead, consider the part of the Hamiltonian accessible to Bob,

$$H'_B \equiv -hZ_B + 2\kappa X_A \otimes X_B. \tag{4}$$

Although $|g\rangle$ is the ground state of the full Hamiltonian H_{AB}, it is an excited state of H'_B. From this perspective, Alice's message enables that Bob extracts energy from an excited state, which is not surprising in itself. What is indeed surprising is the opposite fact: why energy extraction is forbidden from such excited states without Alice's message. The answer lies in the principle of *strong local passivity* (SLP).

Formally, a state ρ is SLP with respect to a Hamiltonian H if no local operation on Bob's side can reduce the system's energy, i.e.,

$$\mathrm{Tr}[H(I_A \otimes G_B)\rho - H\rho] \geq 0 \tag{5}$$

for all completely positive trace-preserving (CPTP) maps G_B. In fact, after Alice's measurement, even though energy is injected into the system, the resulting state is still SLP, thereby preventing Bob's local energy extraction. The classical message from Alice provides Bob with just enough information to break the SLP restriction. In this sense, QET does not literally teleport energy. Instead, it serves as a key to unlock energy that would otherwise remain inaccessible due to SLP.

In constructing this minimal model, four specific requirements have been imposed: (i) ground-state preparation, (ii) shared entanglement, (iii) Alice's measurement commuting with the interaction Hamiltonian, and (iv) classical communication. As the above analysis shows, the first three conditions are sufficient to establish SLP and thus block Bob's energy extraction. However, they are not strictly necessary. In what follows, we demonstrate a related system where the first three conditions are relaxed, yet SLP still emerges. Consequently, Bob still requires Alice's message to perform local energy extraction, thereby broadening the applicability of QET.

3 A FAMILY OF SYSTEMS WITH THE FIRST THREE REQUIREMENTS RELAXED

Here, we provide a method to construct a family of systems that can exhibit SLP with the first three of the above requirements relaxed. We begin with the parameterized spectrum of a general two-qubit Hamiltonian, whose four eigenvalues and eigenvectors are given by

Eigenvalues	Eigenvectors
$\mathscr{E}_4$	$\lvert v_4\rangle = \lvert\psi^\perp\rangle \otimes \lvert\phi^\perp\rangle$
$\mathscr{E}_3$	$\lvert v_3\rangle = \lvert 1\rangle \otimes \lvert\phi\rangle$
$\mathscr{E}_2$	$\lvert v_2\rangle = \lvert 0\rangle \otimes \lvert\phi\rangle$
$\mathscr{E}_1$	$\lvert v_1\rangle = \lvert\psi\rangle \otimes \lvert\phi^\perp\rangle$

where the hierarchy $\mathscr{E}_1 < \mathscr{E}_2 < \mathscr{E}_3 < \mathscr{E}_4$ is assumed. The single-qubit states can be parameterized as (phases omitted for simplicity):

$$\begin{aligned} |\phi\rangle &= \cos(\alpha)|0\rangle + \sin(\alpha)|1\rangle, \\ |\phi^\perp\rangle &= \sin(\alpha)|0\rangle - \cos(\alpha)|1\rangle, \\ |\psi\rangle &= \cos(\beta)|+\rangle + \sin(\beta)|-\rangle, \\ |\psi^\perp\rangle &= \sin(\beta)|+\rangle - \cos(\beta)|-\rangle. \end{aligned} \tag{6}$$

The total Hamiltonian is then

$$H_{AB} = \sum_i \mathscr{E}_i |v_i\rangle\langle v_i|. \tag{7}$$

We set the initial state to $|v_2\rangle$, which is an excited state without entanglement, and let Alice measure her qubit in the Pauli-X basis. The joint post-measurement states are then

$$|+\rangle_A \otimes |\phi\rangle_B, \quad |-\rangle_A \otimes |\phi\rangle_B, \tag{8}$$

each occurring with probability 50%.

For simplicity, we choose the energy spectrum such that $\mathscr{E}_4 = -\mathscr{E}_1 = \mathscr{E} > 0$ and $\mathscr{E}_3 = -\mathscr{E}_2 = \mathscr{F} > 0$. Other choices are possible, but they lead to more general (and more complicated) analyses.

To proceed, we introduce the concept of Bob's *local effective Hamiltonian* (LEH). When Alice's qubit is in state $|i\rangle$, Bob's LEH is defined as

$$H^i_{\mathrm{eff}} = \langle i|H_{AB}|i\rangle. \tag{9}$$

As explained in [XSK25], this LEH has two key roles. First, Bob's energy expectation under H^i_{eff} coincides with the total system energy: if Bob's state is $|j\rangle$, then $\langle j|H^i_{\mathrm{eff}}|j\rangle = \langle H_{AB}\rangle$. Thus, after Alice's measurement, for Bob to extract energy locally, he rotates his state to the ground state of H^i_{eff}. Since this ground state depends on Alice's outcome, the required rotation necessarily depends on Alice's message. This explains the need for conditional operations. Second, when Alice's qubit is frozen to $|i\rangle$, LEH has dynamical effects: Bob's state evolves under H^i_{eff}.

In this model, Bob's LEHs are

$$\begin{aligned} H^+_{\mathrm{eff}} &= -\mathscr{E}\cos(2\beta)\,|\phi^\perp\rangle\langle\phi^\perp|, \\ H^-_{\mathrm{eff}} &= +\mathscr{E}\cos(2\beta)\,|\phi^\perp\rangle\langle\phi^\perp| = -H^+_{\mathrm{eff}}. \end{aligned} \tag{10}$$

Because $\langle\phi|\phi^\perp\rangle = 0$, Bob's post-measurement state $|\phi\rangle$ is an eigenstate of both $H^\pm_{\mathrm{eff}}$. Depending on the sign of $\cos(2\beta)$, it is the ground state in one case and the excited state in the other. Consequently, any local operation by Bob cannot extract energy *on average*: energy extracted in one case is exactly offset by energy injected in the other. The equal mixture of Eq. (8) therefore satisfies the SLP condition, preventing Bob from extracting energy locally after Alice's measurement.

Nevertheless, classical communication restores the possibility of local energy extraction. Upon receiving Alice's message, Bob learns whether his state is the ground state or the excited state. If it is the ground state, he applies the identity operation. If it is the excited state, he applies a π rotation to map the state to $|\phi^{\perp}\rangle$, thereby extracting energy on average from the system.

In addition, the authors of [ASRB$^+$19] provided a necessary and sufficient condition to determine whether a given state is SLP with respect to a Hamiltonian. Using this criterion, one can verify that for arbitrary values of α and β in Eq. (6), the initial state $|v_2\rangle\langle v_2|$ is SLP for H_{AB} on Bob's side. Furthermore, the post-measurement mixed state obtained from Eq. (8) also remains SLP on Bob's side. This construction thus yields a two-parameter family of Hamiltonians exhibiting SLP both for an excited initial state and for the corresponding post-measurement state. Entanglement is absent throughout the entire process. Moreover, Alice's measurement basis (Pauli-X) need not commute with the interaction term in Eq. (7). This demonstrates that the first three requirements mentioned above are relaxed in this construction. The result highlights the necessity of QET for enabling local energy extraction in broader scenarios and applications.

4 CAN CLASSICAL COMMUNICATIONS BE REMOVED FROM QET?

Up to this moment, classical communication (CC) has been regarded as a necessary component of QET. While conditional operations (CO) are indeed essential for breaking SLP, it has not been explicitly proven that CC itself is as essential. This naturally raises the question: can CO be achieved without CC? We show that the answer is affirmative.

Recall the second role of Bob's LEH: it governs dynamical evolution. When Alice's qubit is frozen in the post-measurement state, Bob's qubit evolves under the corresponding LEH. Consequently, the eigenstructure of Bob's qubit depends on Alice's measurement outcome. Suppose now that Bob couples his qubit B to a third qubit C, with the coupling assumed to be weak compared to both the natural frequencies of all qubits and the AB coupling. In this regime, the Rotating Wave Approximation (RWA) can be applied. Under the RWA, the BC interaction Hamiltonian is expressed in the eigenbasis of qubit B, with fast-oscillating terms omitted. As a result, the BC interaction itself becomes dependent on the H_B^{eff}, and thus on Alice's measurement outcome. When the BC interaction is viewed as a general operation on qubit B, this operation thus becomes conditional on Alice's measurement outcome, thereby eliminating the need for classical communication.

Specifically, we consider three qubits interacting via the Hamiltonian

$$H_{ABC} = H_A + V_{AB} + H_B + V_{BC} + H_C. \quad (11)$$

Without loss of generality, suppose Alice's measurement is in the basis $\{|0\rangle, |1\rangle\}$. Bob's two LEHs are then

$$\langle i|_A V_{AB} |i\rangle_A + H_B, \text{ with } i = \{0,1\} \quad (12)$$

and the resulting energy offset achievable through this process is on the order of $|V_{AB}|$.

For the BC coupling, since we want that CC is removed, Bob does not know Alice's outcome and therefore cannot introduce outcome-dependent parameters. Instead, Bob simply switches on the BC interaction immediately after Alice's measurement and turns it off after a fixed time interval. This procedure requires no CC. The interaction with the auxiliary qubit C for a fixed duration constitutes a general local operation on qubit B. If SLP holds, such an operation cannot extract energy from the AB system governed by $H_{AB} \equiv H_A + V_{AB} + H_B$.

Also, since the BC coupling must remain sensitive to changes in the eigenstructure of qubit B, it enforces the condition

$$|V_{BC}| \ll |V_{AB}|, \quad (13)$$

namely, that the BC coupling is weaker than the AB coupling.

One important aspect still needs to be considered. The characteristic timescale for Bob's energy extraction is $T_{BC} \sim 1/|V_{BC}|$, while the intrinsic evolution timescale of the AB system is $T_{AB} \sim 1/|H_{AB}|$. Clearly, this leads to $T_{BC} \gg T_{AB}$, meaning that Bob's energy extraction is much slower than the natural evolution of the AB system. However, one of the main advantages of QET is precisely that energy extraction can occur *faster* than the system's intrinsic evolution. This ensures that QET is a useful protocol for accessing localized energy. Otherwise, once Alice injects energy locally, Bob could simply wait for the energy to propagate naturally to his side and extract it in a time on the order of T_1. If $T_1 \ll T_2$, it would appear unnecessary to invoke QET to break SLP, since waiting would be faster.

This issue can be avoided by choosing the two post-measurement states to be eigenstates of H_{AB}. In this case, Alice's measurement injects energy into the system, but because the post-measurement states are stationary, the injected energy remains localized at Alice's site and does not propagate to Bob. To achieve this, we require a system satisfying three conditions: (i) the post-measurement mixed state is SLP with respect to H_{AB}, so that Bob cannot locally extract energy; (ii) the two post-measurement pure branch states are eigenstates of H_{AB}, so that their mixture remains SLP without further disturbance; (iii) not all of the post-measurement pure branch states are ground states of their corresponding LEHs, which ensures that Bob can, in principle, use QET to break SLP and extract local energy.

As an explicit example, we construct a system where CC can be removed from QET. Defining $H_{AB} \equiv H_A + V_{AB} + H_B$, we consider the Hamiltonian

$$H_{AB} = -Z_A \otimes \mathbb{I}_B + X_A \otimes X_B. \tag{14}$$

Here, for simplicity, we have set $H_B = 0$. A nonzero H_B can also be included without altering the essential physics, as discussed in [XSAK25]. The eigenstructure of this Hamiltonian is given by Table 1.

Eigenvalues	Eigenvectors
$\lambda_4 = \sqrt{2}$	$\lvert v_4\rangle = \lvert\widetilde{-}\rangle \otimes \lvert-\rangle$
$\lambda_3 = \sqrt{2}$	$\lvert v_3\rangle = \lvert\widetilde{1}\rangle \otimes \lvert+\rangle$
$\lambda_2 = -\sqrt{2}$	$\lvert v_2\rangle = \lvert\widetilde{0}\rangle \otimes \lvert+\rangle$
$\lambda_1 = -\sqrt{2}$	$\lvert v_1\rangle = \lvert\widetilde{+}\rangle \otimes \lvert-\rangle$

Table 1: The eigenstructure of H_{AB} in Eq. (14).

Here, we define $|\widetilde{\varphi}\rangle \equiv \exp(i\sigma_y\pi/8)|\varphi\rangle$. The tilde thus denotes a rotation of an arbitrary state $|\varphi\rangle$ around the y-axis.

We choose the initial state to be an equal superposition of $|v_2\rangle$ and $|v_3\rangle$:

$$|\widetilde{+}_A\rangle \otimes |+\rangle_B \equiv \frac{1}{\sqrt{2}}\left(|\widetilde{0}\rangle_A + |\widetilde{1}\rangle_A\right) \otimes |+\rangle_B. \tag{15}$$

Alice measures her qubit A using the projectors $|\widetilde{0}\rangle\langle\widetilde{0}|$ and $|\widetilde{1}\rangle\langle\widetilde{1}|$, leading to the following two possible outcomes, each with probability 50%:

Outcome	Bob's local Hamiltonian
$\lvert v_2\rangle = \lvert\widetilde{0}\rangle \otimes \lvert+\rangle_B$	$H_B^{\text{eff}} = -X_B/\sqrt{2}$
$\lvert v_3\rangle = \lvert\widetilde{1}\rangle \otimes \lvert+\rangle_B$	$H_B^{\text{eff}} = +X_B/\sqrt{2}$

We now revisit the three conditions that we just outlined for removing CC in QET. First, the post-measurement mixed state $\mathbb{I}_A \otimes |+\rangle\langle+|_B$ is SLP for Eq. (14), as can be verified using the method in [ASRB+19]. This prevents Bob from locally extracting energy on average. Second, the two post-measurement states $|v_2\rangle$ and $|v_3\rangle$ are eigenstates of H_{AB}, so the system remains stationary after Alice's measurement and SLP persists. Third, in the traditional QET protocol, Bob can still extract energy once Alice communicates her measurement outcome: if the outcome is $|\widetilde{0}\rangle$, Bob's local Hamiltonian is $\sim -X_B$, where $|+\rangle$ is already the ground state, so he performs the identity operation. If the outcome is $|\widetilde{1}\rangle$, Bob's local Hamiltonian is $\sim X_B$, where $|+\rangle$ is the excited state, so he applies the operation $|+\rangle\langle-| + |-\rangle\langle+|$. In this way, Bob locally extracts energy on average. However, this scheme of energy extraction still requires CC. The question remains: how can we remove CC while retaining CO, as demanded by QET?

As pointed out earlier, the key idea is to implement Bob's local general operation by coupling his qubit B to an auxiliary qubit C. We choose the Hamiltonian

$$V_{BC} = g(X_B \otimes X_C + Y_B \otimes Y_C), \quad H_C = -Z_C/\sqrt{2}, \tag{16}$$

where g is the BC coupling strength. Qubit C is initialized in its ground state $|0\rangle$ to serve as the recipient of energy from qubit B.

We let Alice's qubit A be frozen in its post-measurement state, either $|\widetilde{0}\rangle$ or $|\widetilde{1}\rangle$. This can be achieved, for instance, by repeated projective measurements in the $\{|\widetilde{0}\rangle, |\widetilde{1}\rangle\}$ basis, or by repeatedly applying the operator $|\widetilde{0}\rangle\langle\widetilde{0}| - |\widetilde{1}\rangle\langle\widetilde{1}|$ as a form of bang-bang control, as introduced in [XSAK25]. Afterward, Bob's qubit B evolves under its local effective Hamiltonian $\mp X_B/\sqrt{2}$. In the conventional QET approach, Bob would apply a *fast* local operation (e.g., via classical pulses), which cannot extract energy on average. This corresponds to the regime $g \gg 1$ in Eq. (16). We now demonstrate that when $g \ll 1$, the BC interaction itself becomes dependent on Alice's measurement outcome and automatically implements the desired CO.

When $g \ll 1$ in Eq. (16), the Rotating Wave Approximation (RWA) can be applied, neglecting fast-oscillating terms. Here, the notion of "fast" and "slow" depends on the eigenstructures of H_B^{eff} and H_C.

Case 1: $H_B^{\text{eff}} = -X_B/\sqrt{2}$.

In this case, the BC interaction expands to

$$\begin{aligned} V_{BC} &= 2g|1\rangle\langle 0| \otimes |0\rangle\langle 1| + 2g|0\rangle\langle 1| \otimes |1\rangle\langle 0| \\ &= g(|+\rangle\langle+| + |+\rangle\langle-| - |-\rangle\langle+| - |-\rangle\langle-|) \otimes |0\rangle\langle 1| \\ &\quad + g(|+\rangle\langle+| - |+\rangle\langle-| + |-\rangle\langle+| - |-\rangle\langle-|) \otimes |1\rangle\langle 0|. \end{aligned} \tag{17}$$

Moving to the Heisenberg picture and assuming weak coupling $g \ll 1$, the Heisenberg equations of motion reduce to

$$\begin{aligned} \frac{d}{dt}\mathscr{O}_B(t) &\approx i[H_B^{\text{eff}}, \mathscr{O}_B(t)], \\ \frac{d}{dt}\mathscr{O}_C(t) &\approx i[H_C, \mathscr{O}_C(t)]. \end{aligned} \tag{18}$$

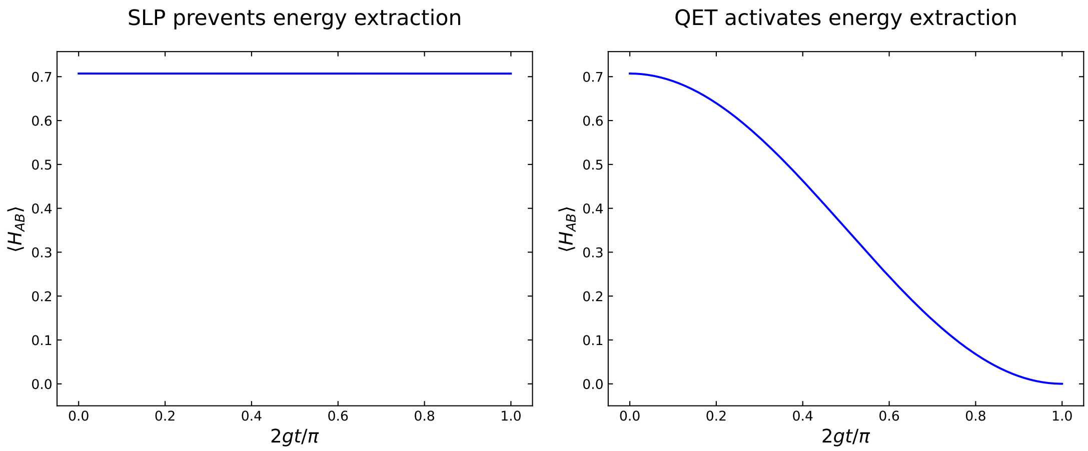

Figure 1: Numerical simulation for quantum energy teleportation without classical communication. Parameters: $g = 0.01$. Alice's operation interval for freezing qubit A: $gt/(5000\pi)$. Left panel: Following Alice's measurement, the AB system enters a stationary SLP state, preventing Bob from extracting local energy. Right panel: When Alice freezes qubit A in the post-measurement state, the BC coupling is activated, enabling Bob's local energy extraction.

This leads to the relations

$$\begin{aligned} &|+\rangle\langle+|_B \sim |-\rangle\langle-|_B \sim 1, \\ &|-\rangle\langle+|_B \sim |1\rangle\langle 0|_C \sim e^{i\sqrt{2}t}, \\ &|+\rangle\langle-|_B \sim |0\rangle\langle 1|_C \sim e^{-i\sqrt{2}t}. \end{aligned} \tag{19}$$

Thus, the slow terms reduce to

$$V_{BC} \approx g|-\rangle\langle+| \otimes |0\rangle\langle 1| + g|+\rangle\langle-| \otimes |1\rangle\langle 0|. \tag{20}$$

Given the initial state $|+\rangle_B|0\rangle_C$, both B and C are in their ground states. This interaction has no effect, corresponding to the identity operation on qubit B.

Case 2: $H_B^{\text{eff}} = +X_B/\sqrt{2}$.

A similar analysis yields

$$\begin{aligned} &|+\rangle\langle+|_B \sim |-\rangle\langle-|_B \sim 1, \\ &|+\rangle\langle-|_B \sim |1\rangle\langle 0|_C \sim e^{i\sqrt{2}t}, \\ &|-\rangle\langle+|_B \sim |0\rangle\langle 1|_C \sim e^{-i\sqrt{2}t}. \end{aligned} \tag{21}$$

leading to

$$V_{BC} \approx g|+\rangle\langle-| \otimes |0\rangle\langle 1| + g|-\rangle\langle+| \otimes |1\rangle\langle 0|. \tag{22}$$

With the initial state $|+\rangle_B|0\rangle_C$, qubit B is excited while C is in its ground state. Choosing the interaction time $t = \pi/(2g)$ results in complete energy transfer from B to C. This corresponds to a π rotation on qubit B.

Consequently, in the weak-coupling regime, the physical process naturally implements a CO on qubit B that precisely matches the operation required for local energy extraction. Specifically, when Alice's outcome is $|\widetilde{0}\rangle$, Bob effectively performs the identity operation; when Alice's outcome is $|\widetilde{1}\rangle$, Bob effectively applies $|+\rangle\langle-| + |-\rangle\langle+|$, exactly as in the conventional QET protocol. Crucially, this is achieved without any CC: the BC interaction automatically adapts to the appropriate form depending on Alice's outcome. In this way, CO is realized without CC, thereby completing the QET protocol while eliminating the need for classical communication.

For the numerical simulation, see Fig. 1. In the left panel, we show that after Alice's measurement, the system remains SLP for Bob, and coupling to a third qubit C does not allow any energy extraction. By contrast, if Alice repeatedly measures her qubit to freeze A in its post-measurement state, the BC coupling breaks SLP and effectively performs the conditional operation required for Bob to extract energy from the system.

5 DISCUSSIONS AND SUMMARY

In summary, we have reviewed the principle of quantum energy teleportation (QET), which was originally thought to rely on four requirements: (i) ground-state preparation, (ii) shared entanglement, (iii) Alice's measurement commuting with the interaction Hamiltonian, and (iv) classical communication (CC). Recent developments have shown that the first three requirements can be relaxed, yet CC appeared to remain indispensable. In this work, we have demonstrated that when Bob's local operation is implemented in the weak-coupling regime, CC itself can also be removed.

In quantum state teleportation (QST), CC is strictly necessary, as information transfer cannot exceed the speed of light. In QET, however, CC can indeed be eliminated without violating relativistic constraints. This is because in QET, energy is not physically transmitted between Alice and Bob; rather, Bob only extracts local energy.

As one potential application of this CC-free QET protocol, we may reinterpret Bob's two qubits as a charger (qubit B) and a battery (qubit C), while Alice's qubit A acts as an external control switch. When Alice performs a measurement, direct energy transfer from B to C remains forbidden due to SLP. However, once Alice freezes the state of her qubit through repeated operations, the BC coupling is effectively activated, enabling energy transfer between B and C. This provides a concrete realization of indirect external control for charging of quantum batteries, as discussed in [XSAK25].

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