Suppressing coherence effects in quantum-measurement based engines

Zhiyuan Lin,1,†, Shanhe Su,1,† Jingyi Chen,1 Jincan Chen,1,‡ and Jonas F. G. Santos2
1Department of Physics, Xiamen University, Xiamen 361005, People’s Republic of China
2Centro de Ciências Naturais e Humanas, Universidade Federal do ABC, Avenida dos Estados 5001, 09210-580 Santo André, São Paulo, Brazil
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The recent advances in the study of thermodynamics of microscopic processes have driven the search for new developments in energy converters utilizing quantum effects. We here propose a universal framework to describe the thermodynamics of a quantum engine fueled by quantum projective measurements. Standard quantum thermal machines operating in a finite-time regime with a driven Hamiltonian that does not commute in different times have the performance decreased by the presence of coherence, which is associated with a larger entropy production and irreversibility degree. However, we show that replacing the standard hot thermal reservoir by a projective measurement operation with general basis in the Bloch sphere and controlling the basis angles suitably could improve the performance of the quantum engine as well as decrease the entropy change during the measurement process. Our results go in direction of a generalization of quantum thermal machine models where the fuel comes from general sources beyond the standard thermal reservoir.

The current development of new devices based on quantum effects has shown that a well-formulated understanding of energy conversion is required. This has been clearly demonstrated through the considerable number of theoretical and experimental advances in quantum thermodynamics [1–4]. It must be highlighted recent progresses in quantum fluctuation relations [5–7], thermodynamics uncertainty relations [8–10], as well as the study of quantum protocols involving non-equilibrium thermal baths [11–14], strong coupling regime [15, 16], and non-Markovian effects [17, 18].

Encompassing the above mentioned results, the study of quantum thermal machines (QTMs) is useful to investigate how specific driving protocols or non-classical baths impact the performance of thermodynamic cycles, i.e., the work extraction (cooling rate) for engine (refrigerator) configurations. In this direction, it is well known that coherence in the energy basis of the working substance leads to the increase of entropy production along the cycle, resulting in the degradation of the performance [19–21]. The theoretical design of quantum machines employing other models of bath beyond the standard Markovian thermal reservoir is also another interesting aspect that has been addressed. For instance, it could be highlighted the use of non-Markovian thermal bath [22–25], finite-size environment [26], and squeezed thermal baths [27–29]. For a quantum thermal machine operating in a finite-time Otto cycle, reaching the limit efficiency with a non-zero extracted power is motivated by realistic applications. From an experimental point of view, realizations of a single-spin quantum engine have been performed in nuclear magnetic resonance (NMR) [30] and in an ensemble of nitrogen vacancy centers in diamond [31], both pointing out the generation of coherence in the energy basis of the working substance. Also, an experimental verification of the fluctuation relation for work and heat in a quantum engine has been recently reported in Ref. [32], showing how correlations between work and heat affect the performance of a finite-time quantum Otto engine.

Apart the standard QTM where the fuel is supplied by a thermal reservoir, a more general type of QTM was proposed by Szilard [33] and differs from the former models in the sense that energy is extracted from a single heat bath by using a feedback mechanism well-known as Maxwell demon [34, 35], putting in evidence that information can effectively work as a fuel in general QTM models [36, 37]. In order to have information flowing into the system in a QTM, we necessarily need to measure the system employing a specific protocol. Since a measurement performed on a quantum system generally alters its state, recent advances have proposed a new QTM type, well-known as measurement-driven engines, in which the measurement protocol itself acts as a fuel and allows for work extraction [38–43]. For standard projective measurements, the system state is entirely collapsed to a specific eigenstate. There is also a special activity concerning the so-called weak measurement [44–46], whose system state is only partially perturbed [47–51]. A natural question that arises in thermodynamic cycles is how to unveil the role played by quantum measurements in the energy conversion and the possibility to suitably engender quantum measurements to enhance the performance of QTMs. In particular for a quantum Otto-like cycle, the finite-time driven unitary strokes in general induce transition between the energy eigenstates of the working substance [19, 52], resulting in an efficiency bellow the Otto limit. However, replacing the standard hot reservoir by a quantum measurement protocol provides another source for transitions which depend essentially on the measurement basis. Thus, from a point of view of the friction induced by transitions between the eigenstates of the working substance [53–55], quantum projective measurements with suitable basis on the Bloch sphere could be understood as a kind of quantum lubricant if it attenuates the degradation effect due to the presence of coherence.

In this work, we are interested in addressing how quantum fluctuations associated with finite-time driven unitary processes and quantum measurements affect the performance of a quantum engine. For this purpose, we consider a modified version of the quantum Otto cycle where the standard hot thermal reservoir is replaced by a quantum projective measurement, providing a different mechanism to fuel the cycle. In order to understand the role played by two kind of quantum fluctuations, we present explicitly expressions for the thermodynamic quantities characterizing the engine, i.e., the extracted work, heat absorbed by the working substance due to the measurement protocol, heat released to the cold source, and efficiency as functions of transition probabilities related to the finite

* These authors contributed equally to this work.
† sushanhe@xmu.edu.cn; jcchen@xmu.edu.cn
time driven Hamiltonian and the measurement scheme. Considering a numerical simulation with parameters employed in NMR setup [56], we show that having a sufficient control over the choice of the measurement basis, it is possible to enhance the work extraction and then the performance of the quantum engine. Since the irreversibility of the cycle is associated with the increase of entropy, we also show that the maximum values of efficiency and extracted work are reached very close to the minimum value of entropy change during the measurement protocol.

The cycle of the engine based on quantum measurement.—The quantum measurement engine employs a particle of spin 1/2 (single qubit) as the working substance. To complete one operating cycle, the engine goes through four strokes, including two adiabatic (unitary) processes, a quantum measurement process, and a thermalization process, as sketched in Fig. 1. The working substance is initially prepared in thermal equilibrium with a heat bath at positive inverse temperature $\beta$, such that its state at time $t = 0$ is given by $\rho_1 = e^{-\beta H_1}/Z_1$ [57, 58], where $H_1 = \hbar^2 \chi_2 / 2 \sigma_z$ is the initial Hamiltonian, $Z_1 = \text{Tr}(e^{-\beta H_1})$ is the partition function, $\hbar$ is the reduced Planck constant, $\omega$ denotes the resonance frequency, and $\sigma_i (i = x, y, z)$ are the Pauli matrices.

During the adiabatic stroke at stage I, a time-modulated radiofrequency field generates a time-dependent Hamiltonian $H_I(t) = \hbar \omega / 2 \cos (\pi \tau s / 2) \sigma_z + \sin (\pi \tau s / 2) \sigma_x$, which clearly does not commute in different times, implying the generation of coherence in the energy basis of the working substance [19]. At $t = \tau$, the working substance changes into state $\rho_2 = U_{\tau,0} \rho_1 U_{\tau,0}^\dagger$ with $U_{\tau,0} = \mathcal{U} e^{-i \int_0^\tau H_I(t)dt}$ being the the time-evolution operator and $\mathcal{U}$ being the time-ordering operator. The work performed on the spin $\langle W_1 \rangle = \text{Tr}(\rho_2 H_2 - \rho_1 H_1)$, where $H_2 = \hbar^2 \chi_2 / 2 \sigma_z$ represents the final Hamiltonian. After the quantum measurement at stage II, the state of the spin is updated to $\rho_3 = \sum_k \eta_k |\chi_k\rangle \langle \chi_k|$, where $\eta_k = |\langle \chi_k| \psi \rangle|^2$ denotes the orthogonal projector associated with the measurement basis $|\chi_1\rangle = e^{-i \phi} \sin (\frac{\pi}{2} s) |\uparrow\rangle - \cos (\frac{\pi}{2} s) |\downarrow\rangle$ and $|\chi_2\rangle = \cos (\frac{\pi}{2} s) |\uparrow\rangle + e^{i \phi} \sin (\frac{\pi}{2} s) |\downarrow\rangle$. In the Bloch sphere representation, $\alpha$ and $\varphi$ are, respectively, the colatitude with respect to the z-axis and the longitude with respect to the x-axis. The total fuel energy provided by quantum measurement $\langle Q_M \rangle = \text{Tr}[H_2 (\rho_3 - \rho_2)]$. During the adiabatic process at stage III, the driving Hamiltonian $H_{II}(t) = H_1(2\tau - t)$ with $t \in [\tau, 2\tau]$. The final state of the second adiabatic stroke $\rho_4 = V_{2\tau,\tau} \rho_3 V_{2\tau,\tau}^\dagger$, where the unitary operator $V_{2\tau,\tau} = \mathcal{U} e^{-i \int_{2\tau}^{\tau} H_I(t)dt}$. The work performed by the external field $\langle W_2 \rangle = \text{Tr}(\rho_4 H_1 - \rho_3 H_2)$. The spin returns to the initial Gibbs state $\rho_1$ for a thermalization process at stage IV. The heat $\langle Q_T \rangle$ flowing into the spin from the bath $\langle Q_T \rangle = \text{Tr}(H_1 \rho_4 - H_1 \rho_4)$.

A more detailed description of the cycle of the quantum measurement engine is shown in Supplementary I. One is capable of proving that $\langle Q_T \rangle$ is always negative, meaning that energy is actually flowing from the working substance into the heat bath (Supplementary II). The thermodynamic cycle is impossible to convert the heat from a single source into work without any other effect, satisfying Kelvin’s statement of the second law of thermodynamics.

The roles of transition probabilities in the performance of the engine.—The net work done by the external agent is

\begin{align}
\langle W \rangle = \langle W_1 \rangle + \langle W_2 \rangle = \hbar \omega [\xi - (\delta - \gamma) (1 - 2\xi)] \tanh \left( \frac{\beta \hbar \omega}{2} \right),
\end{align}

where $\gamma = |\langle \chi_2| U_{\tau,0} | - \rangle_z |^2$ is the transition probability between the basis state $|\chi_2\rangle$ of measurement and the ground eigenstate $| - \rangle_z$ of $H_1 (H_2)$, $\xi = |\langle x| U_{2\tau,\tau} | - \rangle_z |^2$ is the transition probability between the excited eigenstate $| + \rangle_z$ of $H_2$ and the ground eigenstate $| - \rangle_z$ of $H_1$ due to the unitary evolution at stage I, and $\gamma = |\langle +| V_{2\tau,\tau} | - \rangle_z |^2$ is the transition probability between the excited eigenstate $| + \rangle_z$ of $H_1$ and the basis state $|\chi_1\rangle$ of measurement due to the unitary evolution at stage III. The transition probabilities embody the influence of quantum fluctuations and satisfy the principle of microreversibility (Supplementary IV) [61, 62]. For the purpose of extracting work from the engine, we must have $\langle W \rangle < 0$. The fuel energy provided by the measurement process reads

\begin{align}
\langle Q_M \rangle = \frac{\hbar \omega}{2} [(1 - 2\xi) - (1 - 2\delta) (1 - 2\xi)] \tanh \left( \frac{\beta \hbar \omega}{2} \right).
\end{align}

The heat released by the working substance to the cold thermal reservoir in the thermalization process (stage IV) is written as

![Figure 1](image-url). Illustration of the engine based on quantum measurement. (a) The working substance starts in thermal equilibrium with the heat bath. The first stroke is an adiabatic process mediated by a time-dependent Hamiltonian. In the second stroke, an instantaneous projective measurement is performed on the working substance, projecting the single-qubit onto the basis $\{|\chi_1\rangle, |\chi_2\rangle\}$. The third stroke is again a unitary evolution using a time-dependent Hamiltonian. In the fourth stroke, the working substance relaxes to the initial thermal equilibrium state. (b) The evolution of the density matrix during the cycle.
Formally, the measurement basis corresponding to measuring the reason why quantum measurement is able to supply a con-

The performance of the engine is dictated by the constraints $\langle Q_T \rangle \leq 0$ (Supplementary II).

To understand the physics behind the enhancement of $\langle W \rangle$ and $\eta$, we write $\langle W \rangle$ and the quantum fuel $\langle Q_M \rangle$ in terms of the occupation probabilities, i.e.,

$$\langle W \rangle = -\frac{\hbar \omega}{2} (\Delta p_1 - \Delta p_2 + \Delta p_3 - \Delta p_4)$$

$$\langle Q_M \rangle = \frac{\hbar \omega}{2} (\Delta p_2 - \Delta p_3),$$

(5)

Note that since $0 \leq \gamma \leq 1$ and $0 \leq \zeta \leq 1$, the inequality $\frac{1}{2} + \frac{1}{2} \geq 2$ ensures that $\langle Q_T \rangle \leq 0$.

The efficiency is limited by $0 \leq \eta \leq 1$ because of the constraints $\langle Q_T \rangle \leq 0 \leq \langle Q_M \rangle$ and $|\langle Q_T \rangle| \leq |\langle Q_M \rangle|$. With the set of Eqs. (1-4), all the quantum fluctuations induced by the time-dependent Hamiltonian and the measurement protocols are being taken into account, and affect the performance of the engine. In particular, we will show how quantum fluctuations arising from the measurement protocols could be employed (the choice of the measurement angles) in order to suppress the degradation effect due to the coherence, then increasing the efficiency of the cycle.

**Numerical simulation.**—In this section, we illustrate our results with a numerical simulation with feasible parameters employed in NMR setup. Firstly, we note that when $\alpha = \pi/2$ and $\varphi = 0$, the measurement basis commutes with the eigenstate basis of $H_2$. Therefore, no energy is delivered to the working substance, resulting in zero efficiency and null extracted work. The projective quantum measurement inevitably alters the mean energy of the observed system if the measurement basis does not commute with the bare energy basis. This is the reason why quantum measurement is able to supply a continuous source of energy similar to the combustion of a fuel. Formally, the measurement basis corresponding to measuring the single-qubit is a trigonometric function of the colatitude $\alpha$ and longitude $\varphi$. From Fig. (2), we conclude that $\alpha$ and $\varphi$ are two crucial independent parameters to determine the performance of the engine. The working areas of the engine are divided into two separate parts, i.e., $0 \leq \varphi \leq \pi$ and $\pi \leq \varphi \leq 2\pi$. For $0 \leq \varphi \leq \pi$, maximum work output $(-\langle W \rangle)_{\text{max}}$ and efficiency $\eta_{\text{max}}$ appear at different measurement directions. As depicted in Fig. (2), $\langle W \rangle$ qualitatively peaks at $\alpha_W = 1.39$ and $\varphi_W = 2.05$, while $\eta$ reaches its maximum at $\alpha_\eta = 1.45$ and $\varphi_\eta = 2.53$. To obtain a maximum attainable efficiency at a given extracted work, the optimal ranges of the extracted work and efficiency must be constrained by $\alpha_W \leq \alpha \leq \alpha_\eta$ and $\varphi_W \leq \varphi \leq \varphi_\eta$. For $\pi \leq \varphi \leq 2\pi$, the distributions of $\langle W \rangle$ and $\eta$ satisfy antisymmetry with the axis $\alpha = \pi/2$ and translational invariance, i.e., $\langle W \rangle (\alpha, \varphi) = \langle W \rangle (\pi - \alpha, \varphi + \pi)$ and $\eta (\alpha, \varphi) = \eta (\pi - \alpha, \varphi + \pi)$.

To understand the physics behind the enhancement of $\langle W \rangle$ and $\eta$, we write $\langle W \rangle$ and the quantum fuel $\langle Q_M \rangle$ in terms of the occupation probabilities, i.e.,

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$$\langle Q_M \rangle = \frac{\hbar \omega}{2} (\Delta p_2 - \Delta p_3),$$

(5)

where $\Delta p_1 = -\text{Tr} (\rho_1 \sigma_z) = \tanh (\beta \hbar \omega/2)$, $\Delta p_2 = -\text{Tr} (\rho_2 \sigma_z)$, $\Delta p_3 = \langle \chi_1 | \rho_3 | \chi_1 \rangle - \langle \chi_2 | \rho_3 | \chi_2 \rangle$, $\Delta p_4 = -\text{Tr} (\rho_4 \sigma_z) = \langle \chi_1 | \rho_4 | \chi_1 \rangle - \langle \chi_2 | \rho_4 | \chi_2 \rangle$, and $\Delta p_5 = \text{Tr} (\rho_5 \sigma_z)$ are, respectively, the difference in the occupation probability between the ground and excited states of each quantum state. As a result, the efficiency is simplified as

$$\eta = 1 - (\Delta p_1 - \Delta p_4) / (\Delta p_2 - \Delta p_3),$$

which is completely determined by the probability changes caused by the transition coefficients. A conventional quantum engine carries out an adiabatic compression/expansion.

Figure 2. Performance of the engine based on quantum measurement. (a) The extracted work $\langle W \rangle$, (b) efficiency $\eta$, and (c) entropy change $\Delta S$ during the measurement process (stage II) varying with the colatitude $\alpha$ and longitude $\varphi$ on the Bloch sphere, where $\hbar \omega = 1\text{eV}$, $\tau = 10\mu s$, and $\beta = 1/ (\hbar \omega)$. These values are used unless otherwise mentioned specifically in the following discussion.
For a given value \( \phi \) of \( \varphi \), the curves of (a) the work output \(-\langle W \rangle\), input energy \(\langle Q_M \rangle\), efficiency \(\eta\), and the entropy change during the measurement process \(\Delta S\) and (b) the transition probabilities \(\zeta\), \(\delta\), and \(\gamma\) and the differences \(\Delta p_3\) and \(\Delta p_4\) in probability distributions between the ground and excited states varying with the colatitude \(\alpha\). For a given value \(\alpha\) of \(\alpha\), the curves of (c) the work output \(-\langle W \rangle\), input energy \(\langle Q_M \rangle\), efficiency \(\eta\), and the entropy change during the measurement process \(\Delta S\) and (d) the transition probabilities \(\zeta\), \(\delta\), and \(\gamma\) and the difference \(\Delta p_3\) and \(\Delta p_4\) in probability distributions between the ground and excited states varying with the longitude \(\varphi\). In Figs. (a) and (c), the left vertical axis shows values for \(-\langle W \rangle\) and \(\langle Q_M \rangle\), while the corresponding scale of \(\eta\) is on the right vertical axis.

through expanding/reducing the gap between energy levels of the Hamiltonian. The emergence of measurement indicates that the purpose of extracting work may be achieved without changing the energy level spacing.

Apart the energetic exchanges in a quantum cycle, entropic quantities are inherently associated to the irreversibility of the cycle. In this sense, the entropy change of the working substance during the measurement process (state II) directly affects the performance of the engine. Figure 2(c) depicts the entropy change \(\Delta S = S(\rho_3) - S(\rho_2)\) during the measurement process, where \(S(\rho_i) = -Tr(\rho_i \ln \rho_i)\) is the von Neumann entropy of a given state. The entropy change is minimum at \((\alpha_S, \varphi_S) = (1.46, 2.74)\), given the parameters considered in the numerical simulation. The region of large efficiencies matches very well with the region of small entropy changes during the measurement process. This is in agreement with the prediction that decreasing the irreversibility increases the performance of quantum engines. In this sense, we could argue that by choosing an suitable basis for the measurement protocol, it works effectively as a kind of quantum friction, suppressing the degradation effect due to the coherence generated in the stages I and III. The equalities \(S(\rho_1) = S(\rho_2)\) and \(S(\rho_3) = S(\rho_4)\) hold because of the invariant of von Neumann entropy under a unitary evolution. In the fourth stroke of the cycle, one can then confirm that the entropy change \(S(\rho_1) - S(\rho_4)\) caused by the thermalization process is equal to \(-\Delta S\).

In Fig. 3 (a), \(-\langle W \rangle\) \((\eta)\) reaches its limit at \(\alpha_{W'} = 1.25\) \((\alpha_\eta = 1.45)\). However, the input energy \(\langle Q_M \rangle\) is relatively small at the points of \(\alpha_{W'}\) and \(\alpha_\eta\). We also see the behavior of the entropy change during the measurement process, evidencing that it is considerably small for high values of the efficiency. The measurement based engine could generate a greater amount of work at low cost by optimizing the angles of the measurement basis. As the colatitude \(\alpha\) changes, the probability changes \(\Delta p_3\) and \(\Delta p_4\) are the only factors that alter the useful extracted energy and the total energy input. To go a step further, the variations of \(\Delta p_3\) and \(\Delta p_4\) lie on the term associated with \(\zeta\), \(\delta\), and \(\gamma\), as shown in Fig. 3(b). Note that the parameters \(\zeta\), \(\Delta p_3\), and \(\Delta p_2\) remain constant at any given driving time and are not showing up in the graph. The transition probabilities \(\zeta\), \(\delta\), and \(\gamma\) depending on states \(\chi_1\) and \(\chi_2\) contain all information about how quantum measurement plays an important rule in thermodynamics. Figure 3(b) reveals that \(-2\zeta\), \(-2\delta\), and \(-2\gamma\) are convex functions of \(\alpha\), because their derivatives are monotonically non-decreasing. Numerical results also show that the product of \(-2\delta(1-2\gamma)\) and \(-2\zeta\) is a concave function, resulting in the existence of a local maximum of \(\Delta p_3\) \((\Delta p_4)\). When \(\Delta p_3\) takes the peak value, the working substance has the largest probability of being found in the ground state after the measurement and the input energy \(\langle Q_M \rangle\) would be minimum. It is also observed that the gap between \(\Delta p_3\) and \(\Delta p_4\) at \(\alpha_{W'}\) determines the upper bound of \(-\langle W \rangle\).

Finally, we examine how the longitude \(\varphi\) of the measurement basis influences the performance. Figure 3(c) shows that \(-\langle W \rangle\) \(\langle \eta \rangle\) qualitatively peaks at \(\varphi_{W'} = 2.05\) \((\varphi_{\eta} = 2.53)\). In the small-\(\varphi\) regime \((\varphi < \varphi_{W'})\), the difference between \(\Delta p_3\) and \(\Delta p_3\) is enhanced as the increase of \(\varphi\) is attempting to raise \(|1-2\zeta|\) [Fig. 3(d)]. However, in the large-\(\varphi\) regime \((\varphi > \varphi_{W'})\), the decrease of the discrepancy \(\gamma - \delta\) determines the reduction of \(\Delta p_3 - \Delta p_3\) \(-\langle W \rangle\) and \(\Delta p_4 - \Delta p_3\) have a strongly positive, linear relationship. Overall, \(\langle Q_M \rangle\) rapidly decreases with the growth of \(\varphi\), since the increase of the transition probabilities \(\delta\) and \(\zeta\) with respect to increasing \(\varphi\) whistles down \(\Delta p_3\) . The above analysis reveals that the engine under the finite-time adiabatic driving regime realizes the work extraction without changing the spin transition frequency. The angles of measurement basis on the Bloch sphere determine the upper limits on the average work output and efficiency. Again, Fig. 3(c) also shows that the maximum value for the efficiency is found for small values of entropy change during the measurement process.

Conclusions.—Recent advances have shown the possibility of harnessing the energy provided by quantum measurements. We here develop a measurement based single-qubit quantum engine and show how quantum measurement is able to work as a fuel in a quantum cycle. The present model employs a Hamiltonian that does not commute in different times, thus generating coherence in the energy basis of the working substance and then decreasing the performance of the quantum engine. By assuming a sufficient control under the measurement basis angles \(\alpha\) and \(\varphi\), we are able to circumvent the degradation effect due to coherence and increase the extracted work and efficiency. This is verified by comparing the entropy change during the measurement process (stage II) and the efficiency of the engine, showing that high values of efficiency coincide with small values of entropy change. Thus, we could argue that a suitable choice of the measurement basis effectively works as a kind of quantum lubrication, since it suppresses the effect of the coherence produced in stage I and III.

Our results indicate that quantum measurement can be use-
ful to build quantum thermodynamic cycles beyond the standard ones with two thermal baths. Besides, the numerical simulation considers parameters usually employed in NMR, which opens the possibility to experimentally test the measurement based single-qubit quantum engine. We hope that this work can help to unveil the role played by measurement in quantum thermodynamics and its applications.

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