Experimental demonstration of wave-particle duality relation based on coherence measure

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Abstract: Wave-particle duality is a typical example of Bohr’s complementarity principle that plays a significant role in quantum mechanics. Previous studies used the visibility of an interference pattern to quantify the wave property and used path information to quantify the particle property. However, coherence is the core and basis of the interference phenomenon. If we could use coherence to characterize the wave property, the understanding of wave-particle duality would be strengthened. A recent theoretical work [Phys. Rev. Lett. 116, 160406 (2016)] found two relations between quantum coherence and path information. Here, we demonstrate the new measure of wave-particle duality based on two kinds of coherence measures quantitatively for the first time. The wave property, quantified by the coherence in the $l_1$-norm measure and the relative entropy measure, can be obtained via tomography of the target state, which is encoded in the path degree of freedom of the photons. The particle property, quantified by the path information, can be obtained via the discrimination of detector states, which is encoded in the polarization degree of freedom of the photons. Our work may deepen people’s understanding of coherence and provide a new perspective regarding wave-particle duality.

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References and links

Experimental retrodiction of trajectories of single photons in double interferometers

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When a photon passes through an interferometer, quantum mechanics does not provide a clear answer as to its past. Quantum retrodiction is a quantitative theory, which endeavors to make statements about the past of a system based on present knowledge. Quantum retrodiction may be used to analyze the past of a photon, that is, its trajectory. Here we experimentally retrodict the trajectories of single photons in double interferometers by measuring the final state of the photon. A sequence of measurements is made on a photon to determine which path the photon followed, so a series of retrodiction of measurement results can be regarded as a photon trajectory. We obtain information about the partial trajectory and the entire trajectory of the photon. Furthermore, we also observe the effect of different measurements in the extraction of trajectory information. Our experiment highlights the application of retrodiction theory to the study of the photon’s past, and provides potential application in quantum communications.

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I. INTRODUCTION

Prediction is concerned with future events, whereas retrodiction is concerned with past events, that is, making statements about a system’s past based on the present knowledge [1]. The concepts of prediction and retrodiction are particularly relevant to basic processes involved in quantum communications [2]. With the rapid development and interest in quantum communications and quantum cryptography, quantum retrodiction theory is being studied increasingly [2–11]. Quantum retrodiction, as a quantitative theory, is applied to analyze the transmission of signals through an attenuating or amplifying channel in a quantum optical communications network [2,3] and to interpret some experimental phenomena in quantum optics, such as beam splitters [1], photon antibunching [5], and quantum scissors [7], as well as to analyze closed and open system [8,9]. It is also employed in image reconstruction from sparse photocount data [12,13], which not only focuses on a reconstructed image but also provides the full probability distribution function for the intensity at each pixel. Recently, researchers used a weak probe to continuously monitor a superconducting qubit in a microwave cavity, and with that data before and after \( t \) to retrodict the outcome of weak and strong qubit measurement performed at time \( t \) [14].

Here we are interested in retrodiction of the past of a photon in double interferometers. Quantum mechanics does not provide a clear answer to the past of a photon when it passes through an interferometer. Previous theoretical work and which-way experiments presented the past of a photon as a trajectory [15–19]. Subsequently, the study of analyzing the past of a quantum particle according to the weak trace it leaves based on the two-state vector formalism of quantum theory was proposed [20–23]. Especially, two experiments obtained anomalous trajectories of photons not always following continuous trajectories [21,22]. The experiments were performed using an asymmetric Mach-Zehnder interferometer (MZI) with a symmetric MZI inserted into one arm, and used weak interactions to mark the path that photons take through the interferometer, where the experimental results are explained in the framework of the two-state vector formalism of quantum theory [24–26]. Afterwards the analysis of the experiment in [21] using standard quantum optical methods and an amendment version were proposed [27,28]. Here we focus on the past of the photon in the double interferometers based on the quantum retrodiction method, and obtain trajectory information by measuring the final state of the photon.

Suppose a quantum system is prepared in an initial state \( \ket{\Phi} \) and then subjected to a series of measurements \( \{M_1, M_2, \ldots, M_N\} \), but do not read the results [see Fig. 1(a)]. Once a measurement is performed on a quantum system, the state of the system can be changed. Different measurement results correspond to different final states \( \ket{\Psi} \) of the system. We can retrodict the information about measurement results just from the final state of the system. A series of measurement results can be regarded as a trajectory of the quantum system. In this paper, we experimentally retrodict the trajectories of single photons in double interferometers. A sequence of measurements is made on a photon to determine which path the photon followed, so a series of retrodiction of measurement results can be regarded as the trajectory of the photon. We are concerned with that part of or all of the measurement results, i.e., a segment of or the entirety of the photon’s trajectory. Furthermore, we also observe the effect different measurements have on the extraction of the trajectory information.
Coefficient of performance under maximum $\chi$ criterion in a two-level atomic system as a refrigerator

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A two-level atomic system as a working substance is used to set up a refrigerator consisting of two quantum adiabatic and two isochoric processes (two constant-frequency processes $\omega_a$ and $\omega_b$ with $\omega_a < \omega_b$), during which the two-level system is in contact with two heat reservoirs at temperatures $T_h$ and $T_c (< T_h)$. Considering finite-time operation of two isochoric processes, we derive analytical expressions for cooling rate $R$ and coefficient of performance (COP) $\epsilon$. The COP at maximum $\chi (= \epsilon R)$ figure of merit is numerically determined, and it is proved to be in nice agreement with the so-called Curzon and Ahlborn COP $\epsilon_{CA} = \sqrt{1 + \epsilon_C} - 1$, where $\epsilon_C = T_c/(T_h - T_c)$ is the Carnot COP. The high-temperature limit, the COP at maximum $\chi$ figure of merit, $\epsilon^*$, can be expressed analytically by $\epsilon^* = \epsilon_\infty \equiv (\sqrt{9 + 8\epsilon_C} - 3)/2$, which was derived previously as the upper bound of optimal COP for the low-dissipation or minimally nonlinear irreversible refrigerators. Within the context of irreversible thermodynamics, we prove that the value of $\epsilon_\infty$ is also the upper bound of COP at maximum $\chi$ figure of merit when we regard our model as a linear irreversible refrigerator.

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I. INTRODUCTION

A heat device is a heat engine that converts thermal energy into mechanical work, or a refrigerator (heat pump) that is basically a heat engine running backwards. For an endoreversible heat engine working between a hot and a cold reservoir at constant temperatures $T_h$ and $T_c$ (\textless $T_h$), Curzon and Ahlborn (CA) \cite{Curzon1975} found the efficiency at maximum power to be $\eta_{CA} = 1 - \sqrt{T_c/T_h} = 1 - \sqrt{1 - \eta_C}$ with $\eta_C = 1 - T_c/T_h$ the Carnot efficiency. The model of such a heat engine presented by Curzon and Ahlborn gave rise to the birth of finite-time thermodynamics \cite{Curzon1975, Wilcox1993, Ahlborn2005}, a branch of thermodynamics focusing on the optimization on the energy converter that consists of some finite-time thermodynamic processes. The universality and bounds \cite{Sibani2012, Sibani2013, Sibani2014, Sibani2015, Jia2015} of the efficiency at maximum power have been discussed in a large number of studies of heat engines within the context of finite-time thermodynamics.

Unlike in analysis of a heat engine where the power output is always an objective function to determine the optimized efficiency, there are various optimization criteria \cite{Umezawa1991, Sibani2014, Sibani2015, Jia2015} in analysis of optimization of a refrigerator working between two heat reservoirs with constant temperatures $T_h$ and $T_c$. One of these criteria for a refrigerator, which was first proposed by Yan and Chen \cite{Yan2013}, is taking the target function $\chi = \epsilon Q_c/t_{cycle}$, where $Q_c$ is heat absorbed from the cold reservoir, $t_{cycle}$ denotes the cycle time, and $\epsilon = Q_c/W$ with $W$ being the work input per cycle is the coefficient of performance (COP) for refrigerators. This $\chi$-optimization criterion for refrigerators is always adopted and found to be exactly the counterpart \cite{Sh-rres, Wang2013} for the optimization of power output for heat engines. For a low dissipation \cite{Sh-rres, Wang2013} or a minimally nonlinear irreversible \cite{Wang2013} refrigerator, the lower and upper bounds of the COP at maximum $\chi$ figure of merit ($\epsilon^*$) have been found to be $0 \leq \epsilon^* \leq (\sqrt{9 + 8\epsilon_C} - 3)/2$, with $\epsilon_C = T_c/(T_h - T_c)$ being the so-called Carnot COP.

The research into heat engines or refrigerators has been extended from classical to quantum systems \cite{Leggett1987, Zagoskin1997, Zagoskin1999, Blok2001, Blok2002, Blanes2002} over 50 years. This is motivated by exploring the emergence of basic thermodynamic description at the quantum mechanical level, and also by the potential technological applications of these devices \cite{Zagoskin1997, Zagoskin1999, Blok2001, Blok2002, Blanes2002}. In particular, demands for smaller heat devices have been rapidly rising because of miniaturization in experiment \cite{Zagoskin1997, Zagoskin1999} and understanding of quantum thermodynamics \cite{Leggett1987, Zagoskin1997}. The ongoing reduction in system size is approaching the ultimate limit, scaling down these heat devices to a single-particle system, in which quantum properties become significant and have thus to be fully considered.

As quantum versions of classical thermodynamic cycles, quantum thermodynamic cycles have also a set of different cyclic heat device models \cite{Yoshimori2003} working between two heat reservoirs. The quantum Otto cycle, which is a typical one of these models and the quantum analog of the classical Otto cycle used widely in practical heat devices, has been proposed and discussed in a series of papers \cite{Leggett1987, Zagoskin1997, Zagoskin1999, Blok2001, Blok2002, Blanes2002}. The present paper employs a two-level atomic system as a working substance to set up a refrigerator model, which consists of two isochoric and two adiabatic processes and is thus a quantum version of the Otto refrigeration cycle. Based on master equations of stochastic processes, we derive expressions for the cooling rate and power input, which are functions of the time allocation on the two isochors. The objective function $\chi$ is then numerically optimized to determine the optimal COP $\epsilon^*$, which is also analytically expressed as a function of Carnot COP $\epsilon_C$ in the high-temperature limit. Finally, we analyze the COP at maximum $\chi$ figure of merit by taking our model as a linear irreversible refrigerator satisfying the tight-coupling condition.

II. MODEL OF QUANTUM OTTO REFRIGERATION CYCLE

A. Dynamics of occupation probabilities

In the refrigerator model the working substance is a two-level energy system, with ground state $g$ and excited state...
Efficiency at Maximum Power Output of a Quantum-Mechanical Brayton Cycle

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Abstract The performance in finite time of a quantum-mechanical Brayton engine cycle is discussed, without introduction of temperature. The engine model consists of two quantum isoenergetic and two quantum isobaric processes, and works with a single particle in a harmonic trap. Directly employing the finite-time thermodynamics, the efficiency at maximum power output is determined. Extending the harmonic trap to a power-law trap, we find that the efficiency at maximum power is independent of any parameter involved in the model, but depends on the confinement of the trapping potential.

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Key words: quantum-mechanical Brayton engine, harmonic trap, efficiency at maximum power

1 Introduction

Many studies in quantum thermodynamics have been devoted to a number of quantum heat engine or refrigerator models,¹–⁶ which, in fact, are quantum-mechanical extensions⁷–⁹ of classical thermodynamic processes and cycles. Similar to classical thermodynamics, quantum thermodynamics includes all kinds of thermodynamic cycles, such as the Carnot cycle, Otto cycle, Brayton cycle, Stirling cycle, etc. Any quantum heat engine cycle is one of these thermodynamic cycles, and outputs work using the quantum system as its working substance. Because of quantum features of the working substance, novel features have been found in quantum heat engines. A prominent example is a quantum heat engine, which, under some conditions, may surpass the efficiency of a classical Carnot engine cycle.⁸ Additionally, quantum heat engines performing in finite time offer excellent model systems to study the interplay between classical and quantum finite-time thermodynamics.

It is well known that the concept of energy is well-defined in quantum mechanics, temperature a priori is not. Bender et al.⁹ proposed a quantum-mechanical Carnot engine consisting of two isoenergetic and two quantum adiabatic processes, with no inclusion of temperature. Unlike in the conventional quantum heat engine, the working substance of such a quantum heat engine model exchanges heat by coupling to energy baths instead of heat baths. Recently, the quantum-mechanical Carnot engine has been generalized and investigated intensively.⁹,¹¹–¹²,¹⁶–¹⁷,²⁷–²⁸ In a recent paper,²⁸ along with our collaborators, we made a unified and complete discussion of such generalized engine models, including the Carnot cycle, the Otto cycle, the Brayton cycle, the Diesel cycle, etc. However, the time required for completing any one of these engine cycles in Ref. [28] is infinite, indicating that no power can be produced. It is therefore of primary importance to consider these engine models, which undergo finite time and output finite power. In particular, the issue of efficiency maximum power, as a central concern in the study of performance in finite time of heat engines,⁲⁹–³⁴ has attracted much interest for the quantum-mechanical cycle model within context of finite-time thermodynamics. Under such a circumstance, it is meaningful to study the performance in finite time of a quantum-mechanical Brayton engine (QMBE) in which the working substance is coupled with an energy bath instead of a heat bath during one isobaric process.

In this paper, we analyze the performance in finite time of a quantum-mechanical engine cycle of a single particle confined in a one-dimensional (1D) harmonic trap. This quantum heat engine model can be identified as a QMBE since it consists of two quantum adiabatic and two isobaric processes. Heat exchange between the working substance and its surroundings is realized during an isobaric process when the system interacts with an energy bath. The general case when the quantum-mechanical engine works with an arbitrary power-law trap is discussed. In discussing the performance in finite time of the QMBE, we show that the

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Physically reducing the quantum measurement back action in work distributions by a collective measurement

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In quantum thermodynamics, the standard approach to estimating work fluctuations in unitary processes is based on two projective measurements, one performed at the beginning of the process and one at the end. The first measurement destroys any initial coherence in the energy basis, thus preventing later interference effects. To decrease this back action, a scheme based on collective measurements has been proposed by Perarnau-Llobet et al. Here, we report its experimental implementation in an optical system. The experiment consists of a deterministic collective measurement on two identically prepared qubit states, encoded in the polarization and path degree of a single photon. The standard two-projective measurement approach is also experimentally realized for comparison. Our results show the potential of collective schemes to decrease the back action of projective measurements, and capture subtle effects arising from quantum coherence.

Introduction

Quantum coherence lies at the heart of quantum physics. Yet, its presence is subtle to observe, as projective measurements inevitably destroy it. In the context of quantum thermodynamics, this tension becomes apparent in work fluctuations: Whereas projective energy measurements are commonly used to measure them (1, 2), they also lead to work distributions that are independent of the initial coherence in the energy basis. This limitation has motivated alternative proposals for defining and measuring work in purely coherent evolutions (3–18), which include Gaussian (5–8), weak (14–16), and collective measurements (CMs) (17). These different theoretical proposals aim at reducing the back action induced by projective measurements, thus allowing the preservation of some coherent interference effects. This quest is particularly relevant as, when the system is left unobserved, quantum coherence can play an important role in several thermodynamic tasks, e.g., in work extraction (19, 20) and heat engines (21–24). Quantum coherence can be seen as a source of free energy, which is destroyed by projective energy measurements (25, 26).

Here, we report the experimental investigation of reducing quantum measurement back action in work distribution using CMs on two identically prepared qubit states. We implement the proposal of (17) in an all-optical setup, which can be used to efficiently simulate quantum coherent processes. The standard two-projective energy measurement (TPM) scheme (1, 2) to measure work is also experimentally simulated for comparison. The experimental results show the capability of CM to capture coherence effects and reduce the measurement back action, which is quantified as the fidelity between the probability distributions of the final measured and unmeasured states.

Moreover, the potential application of these results goes beyond quantum thermodynamics, as deterministic CMs play a key role in quantum information, being relevant for numerous tasks such as quantum metrology (27, 28), tomography (29, 30), and state manipulation (31).

Results

Theoretical framework

The scenario considered here consists of a quantum state ρ and a Hamiltonian H. The system is taken to be thermally isolated, and it can only be modified by externally driving H. We consider processes in which H is transformed up to H′, and as a consequence, the state evolves under a unitary evolution U, ρ → UρU†. The average energy for this process is given by

$$\langle W \rangle = \text{Tr}(H\rho) - \text{Tr}(H'U\rho U^\dagger)$$

(1)

where the energy difference can be identified with measured average work. However, when one attempts to measure it, the average measured work usually differs from Eq. 1 due to measurement back action (1, 3, 6, 17, 32).

In the standard approach to measuring work in quantum systems (1, 2), one implements two energy measurements, of H and H′, before and after the evolution U. More precisely, expanding the Hamiltonians in the bra-ket representation, as $H = \sum E_i |i\rangle\langle i|$ and $H' = \sum E'_j |j\rangle\langle j|$, the TPM consists of the following:

1) Projective measurement of H on ρ, yielding outcome $E_i$ with probability $p_{i\iota} = \langle \iota | i \rangle$

2) A unitary evolution $U$ of the postmeasured state, $|\iota \rangle \rightarrow U|\iota \rangle$

3) A projective measurement of $H'$ on the evolved state, yielding $E'_j$ with probability $p_{j\iota} = \langle j | U\iota \rangle^2$

The TPM work statistics are then given by the random variable $w_{ij} = E_i - E'_j$, with a corresponding probability $P_{ij} = p_{i\iota}p_{j\iota}$ assigned to the transition $|i\rangle \rightarrow |j\rangle$. The average measured work, $\langle W_{\text{TPM}} \rangle \equiv \sum_i p_{ij} w_{ij}$, can be written as

$$\langle W_{\text{TPM}} \rangle = \text{Tr}(HD_H[p]) - \text{Tr}(H'UD_H[p]U^\dagger)$$

(2)

where $D_H[p]$ is the dephasing operator, removing all the coherence of $p$, which yields a classical mixture of energy states of $H$. Hence, $\langle W_{\text{TPM}} \rangle$ differs from the unmeasured average work in Eq. 1 when $p$ is coherent (and $[H, U H U^\dagger] \neq 0$). Furthermore, the extractable work from $D_H[p]$ is lower than that from $\rho$, as the latter is generally more pure. This can be seen by noting that the nonequilibrium free energy, which characterizes

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1. INTRODUCTION

Quantum coherence, which quantifies the superposition properties of a quantum state, plays an indispensable role in quantum resource theory. A recent theoretical work [Phys. Rev. Lett. 116, 070402 (2016)] studied the manipulation of quantum coherence in bipartite or multipartite systems under the protocol local incoherent operation and classical communication (LQICC). Here we present what we believe is the first experimental realization of obtaining maximal coherence in the assisted distillation protocol based on a linear optical system. The results of our work show that the optimal distillable coherence rate can be reached even in one-copy scenario when the overall bipartite qubit state is pure. Moreover, the experiments for mixed states showed that distillable coherence can be increased with less demand than entanglement distillation. Our work might be helpful in remote quantum information processing and quantum control. © 2017 Optical Society of America

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Experimentally obtaining maximal coherence via assisted distillation process

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Collective measurements on identically prepared quantum systems can extract more information than local measurements, thereby enhancing information-processing efficiency. Although this nonclassical phenomenon has been known for two decades, it has remained a challenging task to demonstrate the advantage of collective measurements in experiments. Here, we introduce a general recipe for performing deterministic collective measurements on two identically prepared qubits based on quantum walks. Using photonic quantum walks, we realize experimentally an optimized collective measurement with fidelity 0.9946 without post selection. As an application, we achieve the highest tomographic efficiency in qubit state tomography to date. Our work offers an effective recipe for beating the precision limit of local measurements in quantum state tomography and metrology. In addition, our study opens an avenue for harvesting the power of collective measurements in quantum information-processing and for exploring the intriguing physics behind this power.