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Non-destructive detection and generation of the Werner state via a dissipative process

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HIGHLIGHTS

- We propose a scheme for nondestructive detection of Werner state.
- We generate a Werner state as a stationary state by pumping the cavity field.
- Accurate controlling of the interaction time is not required in both schemes.

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ABSTRACT

We propose a scheme for the non-destructive detection of an unknown Werner state by detecting the steady-state output intensity of the probe field. Moreover, with a similar mechanism, a Werner state can be generated as a stationary state by pumping the cavity field. The numerical simulations indicate that both the state detection and generation schemes are effective and efficient.

1. Introduction

Quantum entanglement, as a physical resource, plays an essential role in quantum information processing (QIP) [1–3]. In the general case, the best performance of QIP requires the maximally entangled state, for example, the Bell states. However, in practice, the interactions between a system and the environment [A1] will lead the pure system state to degenerate into a mixed one. Thus for practical application, the mixed-state-based QIP has attracted more and more attention. One of the most significant bipartite mixed states is the Werner state [4], which can be considered as a mixture of the four Bell states $|\Psi^{\pm}\rangle = (|1\rangle_1|0\rangle_2 \pm |0\rangle_1|1\rangle_2)/\sqrt{2}$ and $|\Phi^{\pm}\rangle = (|1\rangle_1|1\rangle_2 \pm |0\rangle_1|0\rangle_2)/\sqrt{2}$ (the subscript denotes the label of the qubit). The Werner state is parameterised by a real parameter $x \in [0, 1]$ and can be expressed as

$$\varrho_w = x|\Psi^-\rangle\langle\Psi^-| + (1-x)I_{12}/4, \quad (1)$$

where I_{12} is the identity matrix of the two-qubit Hilbert space. The Werner state is of great importance in entanglement purification [5,6]. It has been shown that, for $x > 1/3$, the Werner state has non-zero entanglement and can be purified to obtain a maximally entangled state; however, for $x < 1/3$ it is a separable state with vanishing entanglement [7]. Moreover,

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even for the separable Werner state with $x \in (0, 1/3]$, it is shown that there is still some other type of quantum correlation, such as quantum discord [8–10].

Generally, the identification of an unknown Werner state, in experiments, is achieved by the so-called quantum-state tomography [11–13], which directly performs the projective measurement on many copies of the state to be measured. However, there is a disadvantage of this technique; that is, after the projective measurements the state to be measured will collapse to one of the measurement bases, which leads the original state to be destroyed and become useless [A2]. To overcome this disadvantage, some schemes for non-destructively detecting a quantum state are proposed [14–17]. Recently, non-demolition measurement of an arbitrary unknown Werner state was realized in a nuclear-magnetic-resonance system [18]. In that scheme the measurements and unitary operations are carried out within the lifetime of the qubits to avoid the errors caused by dissipations. In this article, we propose an alternative scheme to detect an unknown Werner state via cavity mode dissipation in a cavity quantum electrodynamics (cQED) system. The information of the unknown Werner state is extracted by detecting the steady-state intensity of the output field of the cavity mode. Such a cQED system is composed of a fibre-taper-coupled microsphere cavity and two two-level systems. In our discussion, we will choose the atom as an example of the two-level system to demonstrate our scheme. We employ the microsphere cavity in our scheme because it has the advantages of an ultrahigh Q factor, small mode volume and mature fabrication technique [19,20]. Moreover, the efficiency for the input and output process of the microsphere cavity could approach 0.99–0.999 with the help of a tapered fibre [21]. In contrast to the traditional quantum-state tomography technique, the distinct advantage of our scheme is that the unknown Werner state is not disturbed during the whole detection process; as a consequence all the properties of the Werner state, for example, the entanglement, are preserved. Besides, as we are focussing only on the stationary intensity of the output field of the cavity mode, it is not necessary to control the interaction time accurately.

In addition, using a similar mechanism we also propose a scheme to generate a Werner state. Experimentally, generation of a Werner state with polarized photons has been realized via a spontaneous parametric down-conversion technique [22,23]. However, the photonic qubits are not suitable for storing information. Agarwal et al. proposed a scheme for generating the Werner state with atoms, which are perfect candidates for storing information, via atomic collective decay [24]. In our scheme, the Werner state is generated by exciting the quantized whispering-gallery mode (WGM) of the microsphere cavity with a strong driving laser. The induced dissipation effects will lead the atoms evolve to a steady Werner state. This article is organized as follows. The coupling between the microsphere cavity and the tapered fibre provides a dissipative channel that leads the atoms evolve to a stationary state. In Section 2, we demonstrate the scheme of non-destructive detection of a Werner state. In Section 3, we discuss the generation of a Werner state with a similar system. We give out the numerical simulations of the dynamics of the system with the realistic parameters in Section 4. The conclusion is drawn finally.

2. Non-destructive detection of the Werner state

In this section, we will demonstrate the scheme of non-destructive detection of the Werner state explicitly. The experimental set-up is shown in Fig. 1. Two identical two-level atoms, each of which has a ground state $|g\rangle$ and an excited state $|e\rangle$, are equidistantly located near the equator of the microsphere cavity and coupled to the WGM via the evanescent field with the same coupling strength g. Two additional classical driving fields are imposed on the atoms with the Rabi frequency Ω. The Hamiltonian of the whole system can be written as (set $\hbar = 1$ hereinafter)

$$H_0 = \omega_a \sum_{i=1,2} \sigma_i^+ \sigma_i^- + \omega_c a^\dagger a, \tag{2}$$

$$H_{\rm int}^1 = \sum_{i=1,2} (g a^\dagger \sigma_i^- + \Omega \sigma_i^- e^{i\omega_p t}) + H.c., \tag{3}$$

where $\sigma_i^- = |g\rangle_i\langle e|$ is the lowering operator of the ith atom, a is the annihilation operator of the WGM and ω_c, ω_a and ω_p are the frequencies of the WGM, atomic transition and driving laser, respectively. H_0^1 is the free Hamiltonian of the system and $H_{\rm int}^1$ is the interaction Hamiltonian. In a framework rotating at the pump frequency ω_p, the Hamiltonian in the interaction picture with respect to H_0^1 can be written as follows:

$$H_1^1 = g a^\dagger S^- + \Omega S^- + H.c., \tag{4}$$

where we have defined the collective atomic operator $S^\pm = \sum_i \sigma_i^\pm$ which satisfies the usual angular momentum commutation relations

$$[S^+, S^-] = 2S^z, \qquad [S^z, S^\pm] = \pm S^\pm, \tag{5}$$

with $S^z = \sum_i \sigma_i^z$. We restrict our discussion in the resonant case, that is, $\omega_c = \omega_a = \omega_p$. For a non-destructive detection, if the atomic spontaneous emission is considered the Werner state will naturally be destroyed, no matter whether we detect it or not. Therefore the atomic dissipations are assumed to be negligible in our theoretic discussions. The effect of atomic spontaneous emission will be discussed in the numerical simulations. Introducing the cavity dissipation, the system can be described by the master equation $\dot{\rho} = -i[H_1^1, \rho] + \kappa D\rho$, where $D\rho = 2a\rho a^\dagger - a^\dagger a\rho - \rho a^\dagger a$ and κ is the cavity loss rate.