Implementation of unambiguous comparison for unknown pure quantum states with cavity-assisted interaction*

Cheng Liu-Yong(程留永)[a], Wang Hong-Fu(王洪福)[b], Zhang Shou(张 寿)[a)b)†], and Yeon Kyu-Hwang[c]

[a] *Center for the Condensed-Matter Science and Technology, Department of Physics, Harbin Institute of Technology, Harbin* 150001, *China*
[b] *Department of Physics, College of Science, Yanbian University, Yanji* 133002, *China*
[c] *BK21 Program Physics & Department of Physics, College of Natural Science, Chungbuk National University, Cheonju, Chungbuk* 361-763, *Republic of Korea*

(Received 7 September 2012; revised manuscript received 13 November 2012)

We propose two effective schemes for local and remote unknown atomic state comparisons with a cavity-assisted single photon input–output process without any initial entanglement or auxiliary resource. The unambiguous state discrimination is considered using the state comparison process as the basic module. All the implementation schemes here just involve common quantum logic gates and the single qubit measurement. The analysis shows that our schemes are feasible under the current experimental conditions.

Keywords: unambiguous state comparison, atomic qubit, cavity-assisted interaction

PACS: 03.67.–a, 42.50.Dv, 42.50.Pq **DOI:** 10.1088/1674-1056/22/5/050306

1. Introduction

In the current heated research field of quantum information processing and quantum computation, quantum measurement is an indispensable part of determining the final state of the considered quantum system after some unitary transformations. According to the known quantum mechanics theory, if the final output states after an evolution process belong to an orthogonal set, one can determine them with certainty through projection measurement. Whereas when the final probable output states are non-orthogonal to one another, determinate discrimination is far from trivial regardless of whether those states are known or unknown.[1] As a consequence, the discrimination of non-orthogonal quantum states with a success probability of less than one has been developed, which devotes to maximizing the success probability or minimizing the failure one to identify the given quantum state information. The quantum state discrimination for non-orthogonal states always means a lot to secure quantum communication tasks such as quantum cryptography and quantum fingerprinting.[2,3] For example, in Ref. [2], the author proposed a quantum key distribution protocol using the discrimination of two non-orthogonal quantum states as its basis.

The current existing quantum state discrimination strategies mainly fall into three categories: unambiguous discrimination (UD),[4–7] minimum error discrimination (MED),[8] and maximum confidence discrimination (MCD).[9] Unambiguous quantum states discrimination, which is also termed as error-free discrimination, never gives wrong identification results, albeit there is a price that sometimes no explicit information about the states is observed. Due to its special properties, the UD attracted a lot of attention in recent years and was extended to several research fields.[10–14] Considering the states to be discriminated are unknown, we can not draw support from the information of the given states to build an appropriate quantum state discriminator. Such a research project was solved well by Bergou and Hillery for two unknown pure quantum states.[15] In their research, two unknown states are fed into a programmable discriminator as the program states, while a third state that is guaranteed to be in one of the two program states is provided as the data state. Then the quantum state discriminator will reveal which one of the two program states matches the data state with a certain probability of success. This scheme does not give false judgements, but the results are inconclusive to determine the third state sometimes. Inspired by this instructive work, a number of patulous theoretical and experimental schemes have been proposed for the UD of unknown mixed states or qubit states.[16–20]

One special case of quantum state discrimination for unknown states named unambiguous-state comparison has obtained homologous development in the last several years.[21–26] The unambiguous-state comparison considers two unknown quantum states and establishes whether these two states are identical or different through suitable operations and measurements with no error. The first quantum states comparison scheme for two unknown pure states was investigated by Barnett *et al.* in 2003,[21] and it was extended to multiple quantum systems subsequently.[22] In 2007, Bergou and Orszag presented a quantum circuit to unambiguously compare any two

*Project supported by the National Natural Science Foundation of China (Grant Nos. 61068001 and 11264042), the China Postdoctoral Science Foundation (Grant No. 2012M520612), and the Talent Program of Yanbian University of China (Grant No. 950010001).

†Corresponding author. E-mail: szhang@ybu.edu.cn

© 2013 Chinese Physical Society and IOP Publishing Ltd

qubit states with a certain probability of success using only the controlled-NOT (CNOT) gate and single qubit operations.[25] In their scheme, a nonzero component in the antisymmetric subspace of the two qubits implies that the two states are different. And in Ref. [26], an experimental scheme for the unambiguous comparison of optical polarization states was proposed with linear optical elements.

Cavity quantum electrodynamics (QED) concerning the interaction between the quantized optical fields and the trapped atoms in optical or microwave cavities provides a promising candidate of physical system for atomic state quantum information processing.[1,27,28] Encoding qubit information in atomic internal energy levels, the cavity QED device has some typical advantages, such as short interaction time and controllable coupling strength between atoms and photons. In recent years, the interaction of photons and atoms in low-Q optical cavities has been considered explicitly and applied efficaciously to quantum information processing tasks.[29–32] In Refs. [30] and [31], the authors derived a new reflection coefficient equation, and through controlling the single photon to pass through low-Q cavities accomplished the generation of atom entanglement and universal quantum gates. Here we first construct a physical device to implement the comparison of two unknown pure atomic states through the cavity-assisted interaction between atoms and optical fields. This scheme does not require any entanglement resource or ancillary qubit. We also consider the remote implementation of comparing two atomic states by slightly modifying the first device. Subsequently, the nonlocal programmable UD of unknown states is introduced by using the above state comparison approach with the aid of ancillary qubits. The remote implementation of quantum state discrimination and comparison is probably significant to distributed quantum computation and quantum network.

2. Unambiguous comparison and discrimination process of unknown atomic states

2.1. Basic physical model

We begin with a brief review of the single photon input–output process in low-Q cavities present in Refs. [30] and [31]. Consider a neutral atom with the level configuration shown in Fig. 1(b), which has an excited state $|e\rangle$ and two ground states $|g\rangle$ and $|i\rangle$. The atomic level transition between $|i\rangle$ and $|e\rangle$ is resonantly coupled to the vertically polarized photon $|V\rangle$, while level $|g\rangle$ is decoupled to the polarization light. To avoid the adverse effect from the atomic spontaneous emission, information is encoded in ground levels, i.e., $|i\rangle = |0\rangle$ and $|g\rangle = |1\rangle$. Under the assumption of weak excitation condition, the input–output relation regarding the single-sided low-Q optical cavity is expressed as[30]

$$r(\omega_{\rm p}) = \frac{[{\rm i}(\omega_{\rm c}-\omega_{\rm p})-\frac{\kappa}{2}][{\rm i}(\omega_0-\omega_{\rm p})+\frac{\gamma}{2}]+g^2}{[{\rm i}(\omega_{\rm c}-\omega_{\rm p})+\frac{\kappa}{2}][{\rm i}(\omega_0-\omega_{\rm p})+\frac{\gamma}{2}]+g^2}, \tag{1}$$

where κ and γ are the cavity damping rate and the atomic spontaneous emission rate, respectively; $\omega_{\rm c}$, $\omega_{\rm p}$, and ω_0 indicate the cavity field frequency, the incident single-photon frequency, and the atomic transition frequency between levels $|i\rangle$ and $|e\rangle$, respectively; and g is the coupling strength of the atom and the cavity mode. If the input photon encounters an atom in the detuning level, i.e., $g = 0$, then equation (1) changes to

$$r_0(\omega_{\rm p}) = \frac{{\rm i}(\omega_{\rm c}-\omega_{\rm p})-\frac{\kappa}{2}}{{\rm i}(\omega_{\rm c}-\omega_{\rm p})+\frac{\kappa}{2}}. \tag{2}$$

From Eqs. (1) and (2), it can be seen that if a single polarized photon $|V\rangle$ is reflected from a low-Q cavity after running into an atom prepared in $|0\rangle$ or $|1\rangle$, it will experience a phase shift ${\rm e}^{{\rm i}\phi}$ or ${\rm e}^{{\rm i}\phi_0}$. Under the conditions of low-Q factor and weak coupling, choosing $\omega_{\rm c} = \omega_0$, $\omega_{\rm p} = \omega_{\rm c} - \kappa/2$, and $g = \kappa/2$, we have $\phi = \pi$ and $\phi_0 = \pi/2$ from Eqs. (1) and (2), which implies the operation $U = {\rm e}^{{\rm i}\frac{\pi}{2}}|1\rangle\langle 1| + {\rm e}^{{\rm i}\pi}|0\rangle\langle 0|$ on the trapped atom after the cavity-assisted single photon input–output process.[30,31]

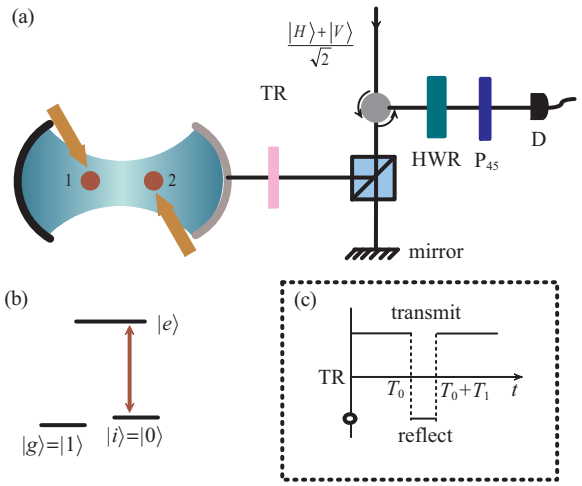


Fig. 1. (color online) Diagrammatic illustration of probabilistic quantum state comparison with single photon input–output process. (a) The implementation device, where PBS stands for a polarizing beam splitter, HWP stands for a half-wave plate, and TR is an optical switch that can control the photon to transmit or reflect. (b) The atom level configuration. (c) Switching on and off time of TR, where T_0 is the time for the single-photon pulse process port-circulator-PBS-TR, while T_1 is the time for TR-cavity-TR-cavity-TR.

2.2. Unambiguous atomic state comparison

To realize the quantum state comparison, as mentioned in Ref. [25], the CNOT gate is a key component. Since it is difficult to carry out a CNOT gate on two atomic qubits directly in the input–output process, decomposing it into one

controlled-Z gate plus two Hadamard gates becomes a feasible alternative. We suppose two atoms 1 and 2 initially prepared in arbitrary single qubit states

$$|\psi\rangle_1 = \alpha_1|0\rangle + \beta_1|1\rangle, \quad |\psi\rangle_2 = \alpha_2|0\rangle + \beta_2|1\rangle, \tag{3}$$

where α_1, α_2, β_1, and β_2 are the normalized constants. Atoms 1 and 2 are confined in a low-Q single-sided optical cavity, as shown in Fig. 1(a). For the single photon input–output process in Eqs. (1) and (2), when the two atoms are in $\{|00\rangle_{12}, |01\rangle_{12}, |10\rangle_{12}\}$ or $|11\rangle_{12}$, the input photon will experience a phase shift $e^{i\phi}$ or $e^{i\phi_0}$. First we use a proper external classic pulse to achieve a Hadamard gate on atom 1. Then an input photon in state $(|H\rangle + |V\rangle)/\sqrt{2}$ passes through a circulator, a polarizing beam splitter (PBS), and an optical switch (TR) to the cavity. Concretely speaking, the circulator distributes the input photon into the correct route, the PBS transmits the horizontal polarization photon $|H\rangle$ and reflects the vertical polarization photon $|V\rangle$, and the TR can control the photon to transmit or reflect with fast switch. So after the photon enters the cavity for the first time, we switch off the TR, which will reflect the photon back to the cavity again, the photon experiences the second coupling with the trapped atom, which results in $U' = -|g\rangle\langle g| + |i\rangle\langle i|$ as $\phi = 2\pi$ and $\phi_0 = \pi$ in Eqs. (1) and (2). Then the photon is reflected from the cavity again and passes through the TR, the PBS, the circulator, a half-wave plate (HWP), and a P_{45}, and finally collected by a photon detector. Here the HWP oriented at 22.5° rotates the photonic polarization by $\pi/4$, and P_{45} is a 45° polarizer projecting the polarization to $(|H\rangle + |V\rangle)/\sqrt{2}$. Hence the whole evolution procedure between the input photon and the two trapped atoms can be represented as

$$\begin{aligned}
& U_{\mathrm{P45}}U_{\mathrm{HWP}}U'H^1\frac{|H\rangle+|V\rangle}{\sqrt{2}}(\alpha_1\alpha_2|00\rangle_{12} + \alpha_1\beta_2|01\rangle_{12} \\
& +\beta_1\alpha_2|10\rangle_{12}\beta_1\beta_2|11\rangle_{12}) \\
\rightarrow\ & U_{\mathrm{P45}}U_{\mathrm{HWP}}\frac{1}{2}\{(|H\rangle+|V\rangle)[(\alpha_1\alpha_2+\beta_1\beta_2)|00\rangle_{12} \\
& +(\alpha_1\beta_2+\beta_1\beta_2)|01\rangle_{12} \\
& +(\alpha_1\alpha_2-\beta_1\alpha_2)|10\rangle_{12}] \\
& +(|H\rangle-|V\rangle)(\alpha_1\beta_2-\beta_1\beta_2)|11\rangle_{12}\} \\
\rightarrow\ & U_{\mathrm{P45}}\frac{1}{\sqrt{2}}\{|H\rangle[(\alpha_1\alpha_2+\beta_1\beta_2)|00\rangle_{12} \\
& +(\alpha_1\beta_2+\beta_1\beta_2)|01\rangle_{12} \\
& +(\alpha_1\alpha_2-\beta_1\alpha_2)|10\rangle_{12}] - |V\rangle(\alpha_1\beta_2-\beta_1\beta_2)|11\rangle_{12}\} \\
\rightarrow\ & \frac{|H\rangle+|V\rangle}{\sqrt{2}}\frac{1}{\sqrt{2}}[(\alpha_1\alpha_2+\beta_1\beta_2)|00\rangle_{12} \\
& +(\alpha_1\beta_2+\beta_1\beta_2)|01\rangle_{12} \\
& +(\alpha_1\alpha_2-\beta_1\alpha_2)|10\rangle_{12} - (\alpha_1\beta_2-\beta_1\beta_2)|11\rangle_{12}].
\end{aligned} \tag{4}$$

After the photon detector is triggered, we perform the Hadamard gates on atoms 1 and 2 respectively using classic pulses. It follows that the final atomic state is given by

$$\begin{aligned}
|\Phi\rangle_{12} = & \frac{1}{\sqrt{2}}[(\alpha_1\alpha_2+\beta_1\beta_2)|00\rangle_{12} \\
& +(\alpha_1\alpha_2-\beta_1\beta_2)|01\rangle_{12} \\
& +(\alpha_1\beta_2+\beta_1\alpha_2)|10\rangle_{12} \\
& -(\alpha_1\beta_2-\beta_1\alpha_2)|11\rangle_{12}].
\end{aligned} \tag{5}$$

It is evident from the equation above that if the measurement result of atoms 1 and 2 is $|11\rangle$, we can declare that the two states are not the same. While the other measurement results $|00\rangle, |01\rangle$, and $|10\rangle$ lead to inconclusive judgement. So the probability of unambiguous comparison is

$$P = \frac{1}{2}|\alpha_1\beta_2 - \beta_1\alpha_2|^2. \tag{6}$$

Since the two given states are completely unknown, we should average P over all possible inputs on the Bloch sphere, getting $P = 1/2 \times 1/2 = 1/4$.

Using the same principle, we can accomplish a remote quantum state comparison through simply modifying the previous device in Fig. 1(a). Consider two atoms with the atomic energy level structure shown in Fig. 1(b) confined in two spatially separated cavities as shown in Fig. 1. The optical elements TR, PBS, and P_{45} have the same functions as those in Fig. 1(a), but the HWP here plays the role of a Hadamard gate for the photon polarization state. If atoms 1 and 2 are prepared in arbitrary single qubit states as Eq. (3) and the input single photon is in state $|H\rangle$, the comparison process is as follows.

First we perform a Hadamard gate on atom 1 with a classical pulse. Then the circulator transmits the input photon to HWP, PBS1, and cavity 1. After interacting with atom 1 twice, resulting in the operator U', the reflected photon from cavity 1 is transmitted to PBS2 and cavity 2. Then the single photon experiences the same interaction as that in cavity 1. Finally, the input photon encounters P_{45} and is detected by a conventional photon detector. Once the detector clicks, we perform the Hadamard gates on atomic qubits 1 and 2 again respectively. Right now the remote two atomic states are transformed from Eq. (3) to Eq. (5). The remote unambiguous state comparison can be accomplished by measuring the atomic states with a successful probability of 1/4. It is necessary to note that in our scheme, the atomic transition between $|i\rangle$ and $|e\rangle$ is resonantly coupled to the vertically polarized photon $|V\rangle$, which makes the device here simpler and easier to realize than that in Fig. 2 of Ref. [31] as some optical wave plates are not needed.

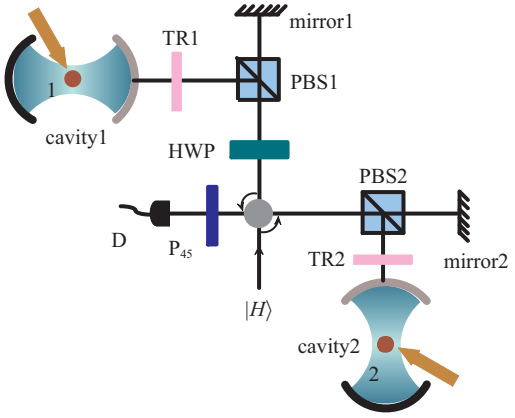


Fig. 2. (color online) Diagrammatic illustration of state comparison for two atoms in separated cavities. The function of each component is similar to that in Fig. 1, the operations are specified in the text.

2.3. Unambiguous state discrimination with state comparison

Extending the remote state comparison device, we can also realize a kind of unambiguous state discrimination. In Ref. [15], the authors presented a programmable discriminator with three input ports for unknown pure quantum states. Two input ports provide two unknown states as the program qubits, and the third port provides a state as the data state which is guaranteed to be in one of the two program states. After proper operations and measurements, the discriminator will tell which one of the program states matches the data state with a certain probability. In a sense, that UD is equivalent to comparing the data state with the two program states separately. However from the above comparison schemes, we can see that the two states to be compared are destroyed by measurements at the end of the comparison process. So we should first split the data state into two qubits. As illustrated in Ref. [25], the quantum state splitting can be accomplished by a Fredkin gate with the aid of two ancillary qubits. The integrated quantum circuit for the state discriminator is shown in Fig. 3.

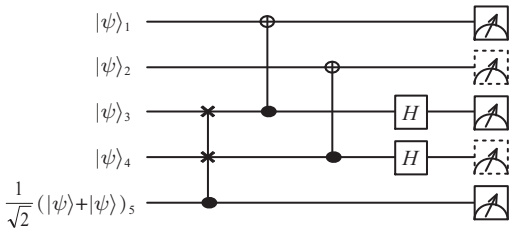


Fig. 3. Quantum circuit of unambiguous state discrimination for unknown atomic states.[25]

Concretely speaking, apart from the given three qubits, we introduce two ancillary qubits in states $|0\rangle$ and $(|0\rangle+|1\rangle)/\sqrt{2}$ respectively. Note here that the additional qubits are also atomic states and trapped in low-Q optical cavities as depicted in Fig. 2. Through a cavity-assisted input–output process, the Fredkin gate has been proposed determinately in Ref. [33]. Thus the logical operations in Fig. 3 are all feasible with the cavity-assisted interaction. Assume the data state has the form

$$|\psi\rangle_3 = \gamma|0\rangle + \eta|1\rangle, \tag{7}$$

and two program states are given in Eq. (3). The whole output state after operations in Fig. 3 is

$$\begin{aligned}
&H_4H_3\mathrm{CNOT}_{42}\mathrm{CNOT}_{31}F_{543}|\psi\rangle_1|\psi\rangle_2|\psi\rangle_3 \\
&\otimes|0\rangle_4\otimes\frac{(|0\rangle+|1\rangle)_5}{\sqrt{2}} \\
&= \frac{1}{\sqrt{2}}\left(\frac{\alpha_1\gamma+\beta_1\eta}{\sqrt{2}}|00\rangle_{13}+\frac{\alpha_1\gamma-\beta_1\eta}{\sqrt{2}}|01\rangle_{13}\right. \\
&\left.+\frac{\alpha_1\eta+\beta_1\gamma}{\sqrt{2}}|10\rangle_{13}+\frac{\beta_1\gamma-\alpha_1\eta}{\sqrt{2}}|11\rangle_{13}\right) \\
&\times|\psi\rangle_2\frac{(|0\rangle+|1\rangle)_4}{\sqrt{2}}|0\rangle_5 \\
&+\frac{1}{\sqrt{2}}\left(\frac{\alpha_2\gamma+\beta_2\eta}{\sqrt{2}}|00\rangle_{24}+\frac{\alpha_2\gamma-\beta_2\eta}{\sqrt{2}}|01\rangle_{24}\right. \\
&\left.+\frac{\alpha_2\eta+\beta_2\gamma}{\sqrt{2}}|10\rangle_{24}+\frac{\beta_2\gamma-\alpha_2\eta}{\sqrt{2}}|11\rangle_{24}\right) \\
&\times|\psi\rangle_1\frac{(|0\rangle+|1\rangle)_3}{\sqrt{2}}|1\rangle_5,
\end{aligned} \tag{8}$$

where F_{543} indicates a Fredkin gate with qubit 5 as the controlled qubit and qubits 3 and 4 as the swapped qubits. Next, we measure the qubits to confirm which of the program states is matched by the data state. From Eq. (8), it can be seen that measuring all the five qubits is not necessary. We should measure the fifth qubit first and then the first four qubits optionally, that is, if the measuring result of qubit 5 gives $|0\rangle$, we just need to measure qubits 1 and 3. Whereas if the measuring result of qubit 5 gives $|1\rangle$, qubits 2 and 4 need to be measured. And the combination $|110\rangle_{135}$ implies that the data state matches $|\psi\rangle_2$, while $|111\rangle_{245}$ corresponds to $|\psi\rangle = |\psi\rangle_1$. Assume the priori probabilities of the two possible input states are ξ_1 and ξ_2, the total successful probability of the UD is

$$P' = \xi_1\frac{|\beta_1\gamma-\alpha_1\eta|^2}{4}+\xi_2\frac{|\beta_2\gamma-\alpha_2\eta|^2}{4}. \tag{9}$$

Similarly, we average P' over all possible inputs on the Bloch sphere, getting 1/8.

3. Discussion and summary

In this paper, we propose schemes for local and remote pure quantum state comparisons with cavity-assisted interaction. The quantum state information is encoded on atomic ground levels to restrain the effect of spontaneous emission. Then unambiguous state discrimination is considered using the state comparison process as the elementary unit. It is necessary to note that the successful probabilities of the comparison and the discrimination schemes are not optimal but

close to the optimal values according to Ref. [15]. Here we want to emphasize that the comparison and the discrimination schemes can be accomplished with fewer and simpler quantum logic gates. Most previous implementation schemes of quantum state comparison and discrimination mainly concentrate on optical qubits.[16,26] Furthermore, considering the atomic states as information stored qubits and photons as flying qubits, the cavity-assisted interaction device is easy to extend to several atoms in spatially separated cavities.

In the actual experiment, fast and controlled switchings may be difficult to achieve. But the TR here is only controlled by a computer to open or close rather than switching the optical path of the photon intricately. And in our proposal, the high time precision of the TR is not needed because its working state always continues for some time as shown in Fig. 1(b). In addition, the photon loss due to the cavity mirror absorption and scattering, the fiber absorption, and the inefficiency of the detector will bring error to this scheme. However, the current fabrication techniques can suppress the photon leakage and make it negligible compared with the main cavity decay into the input–output modes. Moreover, the successful generation is reflected in triggering the photon detector. So the photon loss will just affect the success efficiency rather than the fidelity. It is fortunate that the recent experimental technology can generate 300000 high-quality single photons within 30 s,[34] which ensures that our scheme can be accomplished fast and near determinately. In the present schemes, the weak excitation condition is required for effective photon reflection. And this condition can be satisfied by high quality single-photon sources already achieved.[35] Finally, it should be noted that we have discussed the single photon input–output process in the above schemes, while the experimental setup can also be designed with a weak coherent light pulse and the homodyne measurement as expounded in Refs. [36]– [39]. In short, our implementation devices of state comparison and discrimination are feasible under the current technical conditions.

References

[1] Nielsen M A and Chuang I L 2000 *Quantum Computation and Quantum Information* (Cambridge: Cambridge University Press)
[2] Bennett C H 1992 *Phys. Rev. Lett.* **68** 3121
[3] Buhrman H, Cleve R, Watrous J and Wolf R de 2001 *Phys. Rev. Lett.* **87** 167902
[4] Ivanovic I D 1987 *Phys. Lett. A* **123** 257
[5] Dieks D 1988 *Phys. Lett. A* **126** 303
[6] Peres A 1988 *Phys. Lett. A* **128** 19
[7] Jaeger G and Shimony A 1995 *Phys. Lett. A* **197** 83
[8] Helstrom C W 1976 *Quantum Detection and Estimation Theory* (New York: Academic Press)
[9] Croke S, Andersson E, Barnett S M, Gilson C R and Jeffers J 2006 *Phys. Rev. Lett.* **96** 070401
[10] Chefles A and Barnett S M 1998 *Phys. Lett. A* **250** 223
[11] Rudolph T, Spekkens R W and Turner P S 2003 *Phys. Rev. A* **68** 010301
[12] Bergou J A, Feldman E and Hillery M 2006 *Phys. Rev. A* **73** 032107
[13] Chen L B, Jin R B and Lu H 2008 *Chin. Phys. B* **17** 778
[14] Pang S and Wu S 2009 *Phys. Rev. A* **80** 052320
[15] Bergou J A and Hillery M 2005 *Phys. Rev. Lett.* **94** 160501
[16] Probst-Schendzielorz S T, Wolf A, Freyberger M, Jex I, He B and Bergou J A 2007 *Phys. Rev. A* **75** 052116
[17] He B, Bergou J A and Ren Y 2007 *Phys. Rev. A* **76** 032301
[18] Wu X and Gong Y 2008 *Phys. Rev. A* **78** 042315
[19] Herzog U and Bergou J A 2008 *Phys. Rev. A* **78** 032320
[20] Wu X, Yu S and Zhou T 2009 *Phys. Rev. A* **79** 052302
[21] Barnett S M, Chefles A and Jex I 2003 *Phys. Lett. A* **307** 189
[22] Chefles A, Andersson E and Jex I 2004 *J. Phys. A: Math. Gen.* **37** 7315
[23] Kleinmann M, Kampermann H and Bruß D 2005 *Phys. Rev. A* **72** 032308
[24] Sedlák M, Ziman M, Budžek V and Hillery M 2008 *Phys. Rev. A* **77** 042304
[25] Bergou J A and Orszag M 2007 *J. Opt. Soc. Am. B* **24** 384
[26] Lin Q 2009 *Chin. Phys. B* **18** 51
[27] Walther H, Varcoe B T H, Englert B G and Becker T 2006 *Rep. Prog. Phys.* **69** 1325
[28] Sauer J A, Fortier K M, Chang M S, Hamley C D and Chapman M S 2004 *Phys. Rev. A* **69** 051804
[29] Dayan B, Parkins A S, Aoki T, Ostby E P, Vahala K I and Kimble H J 2008 *Science* **319** 1062
[30] An J H, Feng M and Oh C H 2009 *Phys. Rev. A* **79** 032303
[31] Chen Q and Feng M 2009 *Phys. Rev. A* **79** 064304
[32] Pan G Z, Yang M and Cao Z L 2009 *Chin. Phys. B* **18** 2319
[33] Song J, Xia Y and Song H S 2009 *Europhys. Lett.* **87** 50005
[34] Hijlkema M, Weber B, Specht H P, Webster S C, Kuhn A and Rempe G 2007 *Nat. Phys.* **3** 253
[35] Shields A J 2007 *Nat. Photon.* **1** 215
[36] Wang B and Duan L M 2005 *Phys. Rev. A* **72** 022320
[37] Xue P and Xiao Y F 2006 *Phys. Rev. Lett.* **97** 140501
[38] Huang X H, Lin X M, Lin G W, Chen Z H and Tang Y X 2008 *Chin. Phys. B* **17** 4382
[39] Mei F, Yu Y F, Feng X L, Zhang Z M and Oh C H 2010 *Phys. Rev. A* **82** 052315