Partially dark optical molecule via phase control

Z. H. Wang$^{1,2,3}$ and Yong Li$^{3,4,5,*}$

$^1$Center for Quantum Sciences and School of Physics, Northeast Normal University, Changchun 130024, China
$^2$Center for Advanced Optoelectronic Functional Materials Research, and Key Laboratory for UV-Emitting Materials and Technology of Ministry of Education, Northeast Normal University, Changchun 130024, China
$^3$Beijing Computational Science Research Center, Beijing 100094, China
$^4$Synergetic Innovation Center of Quantum Information and Quantum Physics, University of Science and Technology of China, Hefei 230026, China
$^5$Synergetic Innovation Center for Quantum Effects and Applications, Hunan Normal University, Changsha 410081, China

We study the tunable photonic distribution in an optical molecule consisting of two linearly coupled single-mode cavities. With the inter-cavity coupling and two driving fields, the energy levels of the optical-molecule system form a closed cyclic energy-level diagram, and the phase difference between the driving fields serves as a sensitive controller on the dynamics of the system. Due to the quantum interference effect, we can realize a partially dark optical molecule, where the steady-state mean photon number in one of the cavities achieves zero even under the external driving. And the dark cavity can be changed from one of the cavities to the other by only adjusting the phase difference. Furthermore, we show that when one of the cavities couples with an atomic ensemble, it will be dark under the same condition as that without atoms, but the condition for the other cavity to be dark is modified.

PACS numbers: 42.50.Pq, 42.50.Ex, 42.50.Pq

I. INTRODUCTION

Coherent control of photons is nowadays one of the central topics in quantum optics and quantum information processing. Usually, the photons are confined in small volumes of cavities with low dissipation, in order to promote their controllability and enhance their interaction with matters such as atoms. Besides, it is convenient to couple the cavities each other to form controllable quantum network and construct quantum device. For example, the coupled-cavity array with doped defects can be used to realize the single-photon transistor or router, and the system can also be applied to simulate the quantum phase transition in strong correlated systems.

In recent years, the coherent control of photons in a simple system of two coupled cavities (that is, an optical molecule), has invoked a lot of research interests, including for example, the photon blockade, state transfer, non-equilibrium dynamics, coherent polariton, and unidirectional photonic transport. However these above works appear in the systems of optical molecules with the assistance of some nonlinear interactions, such as the Kerr interaction. It naturally inspires us to investigate the photonic control in the optical-molecule system up to only the linear terms in the effective interactions.

In this paper, we study the coherent control of mean photon numbers in the cavities of an optical molecule when it reaches its steady state. In such a system, one can construct a closed cyclic diagram for the energy levels (e.g., the lowest three energy ones) with the inter-cavity coupling and two classical fields which drive the two cavities respectively. And the phase difference between the two driving fields serves as a sensitive controller for physical phenomenon. Due to the quantum interference effect, we show that the partially dark optical molecule can be realized: the steady-state mean photon number of any of the two cavities can be zero (i.e., the cavity is dark since it achieves its steady vacuum state without considering the vacuum fluctuation) even under external driving. Furthermore, the dark cavity can be modified from one cavity to the other by only adjusting the phase difference, which can be easily controlled in experiments.

Furthermore, we consider the case of adding an ensemble of identical atoms to interact with one of the cavities of the optical molecule. By means of the bosonization process of the low atomic collective excitations, we keep effectively only the linear effects of atom-cavity interaction and obtain analytically the steady-state values of the photon numbers in the cavities. Similar to the situation without atomic ensemble, we can also prepare the partially dark optical molecule with zero mean photon number in either of the cavities by tuning the phase difference between the two driving fields. Moreover, compared with the case without atoms, the condition for the cavity which couples to the atomic ensemble is not changed but that for the other cavity is significantly modified.

The rest of the paper is organized as follows. In Sec. I, we present the Hamiltonian and the steady-state values...
of the photon numbers in the cavities of the optical-molecule system. The condition to realize partially dark optical molecule is discussed in Sec. III. We discuss in Sec. IV the realization of partially dark optical molecule in the situation where one of the cavities is coupled with an ensemble of identical atoms. A brief conclusion is given in Sec. V.

II. THE HAMILTONIAN AND STEADY STATE

The optical-molecule system under consideration is schematically shown in Fig. 1(a). The two single-mode cavities couple to each other, and the Hamiltonian can be written as (here and after $\hbar = 1$

$$H = \omega_1 a_1 \dagger a_1 + \omega_2 a_2 \dagger a_2 + J(a_1 \dagger a_2 + a_2 \dagger a_1) + (\lambda_1 a_1 e^{i\omega_1 t} + \text{H.c.}) + (\lambda_2 a_2 e^{i\omega_2 t} + \text{H.c.}),$$

(1)

where $a_1$ ($a_2$) is the annihilation operator of cavity mode 1 (2) with resonance frequency $\omega_1$($\omega_2$). $J > 0$ is the coupling strength between the two cavity modes. Furthermore, we introduce a pair of external classical field with the same frequency $\omega_d$ to drive the two cavities respectively. $\lambda_1$ ($\equiv |\lambda_1| e^{i\phi}$) and $\lambda_2$ ($\equiv |\lambda_2|$) are the driving strength for the cavities respectively and $\phi$ is the phase difference of the two driving fields, which can be tuned freely in the regime $-\pi \leq \phi \leq \pi$. In the rotating frame with respect to the driving frequency $\omega_d$, the Hamiltonian becomes

$$\mathcal{H} = \Delta_1 a_1 \dagger a_1 + \Delta_2 a_2 \dagger a_2 + J(a_1 \dagger a_2 + a_2 \dagger a_1) + |\lambda_1|(a_1 e^{i\phi} + a_1 \dagger e^{-i\phi}) + |\lambda_2|(a_2 + a_2 \dagger),$$

(2)

where $\Delta_1(2) = \omega_1(2) - \omega_d$ is the detuning between the cavity 1 (2) and the driving field. The dynamics of the system can be described by the Heisenberg-Langevin equation (neglecting the fluctuations)

$$\dot{A} = MA + B,$$

(3)

where $A = (a_1, a_2)^T$, $B = -i(|\lambda_1| e^{-i\phi}, |\lambda_2|)^T$, and

$$M = \begin{pmatrix} -(i\Delta_1 + \frac{\gamma_1}{2}) & -iJ \\ -iJ & -(i\Delta_2 + \frac{\gamma_2}{2}) \end{pmatrix}$$

(4)

with $\gamma_i(2) > 0$ being the decay rate of cavity mode 1 (2). The steady-state values of the system are given by

$$\alpha_1 = \langle a_1 \rangle = -\frac{e^{-i\phi} (R_1 + iI_1)}{\det(M)},$$

(5)

$$\alpha_2 = \langle a_2 \rangle = -\frac{(R_2 + iI_2)}{\det(M)},$$

(6)

where

$$R_1 \equiv |\lambda_2| J \cos \phi - |\lambda_1| \Delta_2, \quad I_1 \equiv \frac{|\lambda_1| \gamma_2}{2} + |\lambda_2| J \sin \phi,$$

(7)

$$R_2 \equiv |\lambda_1| J \cos \phi - |\lambda_2| \Delta_1, \quad I_2 \equiv \frac{|\lambda_2| \gamma_1}{2} - |\lambda_1| J \sin \phi.$$  

(8)

It is obvious that the phase difference $\phi$ plays a significant role in controlling the photon numbers in the two cavities. The phase dependent dynamics is ascribed to the quantum interference effect with different transition paths. As shown in Fig. 1(b), the driving field of strength $\lambda_1$ induces the transitions $|0, 0 \rangle \rightarrow |1, 0 \rangle \rightarrow |2, 0 \rangle$ and $|0, 1 \rangle \rightarrow |1, 1 \rangle$, and the driving field of strength $\lambda_2$ induces the transitions $|0, 0 \rangle \rightarrow |0, 1 \rangle \rightarrow |0, 2 \rangle$ and $|1, 0 \rangle \rightarrow |1, 1 \rangle$ with $|m, n \rangle$ representing $m$ photons in cavity 1 and $n$ photons in cavity 2. Meanwhile, the direct inter-cavity coupling $J$ induces the transitions $|1, 0 \rangle \rightarrow |0, 1 \rangle$ and $|2, 0 \rangle \rightarrow |1, 1 \rangle \rightarrow |0, 2 \rangle$. Therefore, a closed cyclic transition forms for any subspace $\{|m, n \rangle, |m, n + 1 \rangle, |m + 1, n \rangle \}$ (for example, see the states in the dashed rectangle frame for the case of $m = n = 0$) and the relative total phase of the loop $\phi$ will essentially influence the steady state of the system. However, when any of the driving fields is shut down, the closed transition disappears and the phase difference $\phi$ will take no effect in controlling the average photon numbers in the cavities. This fact can also be observed in Eqs. (5, 6), which show that both $|\alpha_1|^2$ and $|\alpha_2|^2$ are independent of the phase difference $\phi$ when $|\lambda_1| = 0$ or $|\lambda_2| = 0$. Actually, the similar closed cyclic energy-level diagram can also be found in many other systems, such as superconducting artificial atom, chiral molecule, cavity-QED system, and cavity optomechanical system, in which the phase control to quantum phenomenon has attracted much attention.

In Fig. 2 we plot the average photon numbers $|\alpha_1|^2$ and $|\alpha_2|^2$ as functions of the phase difference $\phi$. It is interesting that, even in the presence of the driving fields, we can still achieve the regime in which $|\alpha_1|^2 = 0$ or $|\alpha_2|^2 = 0$. It implies that we can realize the partially dark optical molecule, i.e., one of the cavities will stabilize in its vacuum state, and thus will be named as dark cavity in the following. The parameter condition to realize such
both satisfied.

Under these parameters, the conditions in Eqs. (10,12) are both satisfied.

a partially dark optical molecule will be discussed in the next section.

III. REALIZATION OF PARTIALLY DARK OPTICAL MOLECULE

In the last section, we have shown that by adjusting the phase difference between the two driving fields, one of the cavities can be tuned to be in its steady vacuum state. In this section, we will give the conditions for realizing such a partially dark optical molecule.

First, we seek the conditions for the average photon number of the cavity mode 1 being zero ($\alpha_1 = 0$). As shown in Eqs. (517), this requires $R_1 = I_1 = 0$, which yields

$$\cos \phi = \frac{\lambda_1 |\Delta_1|}{|\lambda_2| J}, \quad \sin \phi = \frac{-\lambda_1 \gamma_2}{2 |\lambda_2| J}. \quad (9)$$

The above equation implies

$$|\lambda_2|^2 J^2 = |\lambda_1|^2 (\Delta_1^2 + \frac{\gamma_2^2}{4}). \quad (10)$$

Similarly, the conditions for $\alpha_2 = 0$ can be expressed as

$$\cos \phi = \frac{\lambda_2 |\Delta_2|}{|\lambda_1| J}, \quad \sin \phi = \frac{\lambda_2 \gamma_1}{2 |\lambda_1| J}. \quad (11)$$

which implies

$$|\lambda_1|^2 J^2 = |\lambda_2|^2 (\Delta_2^2 + \frac{\gamma_1^2}{4}). \quad (12)$$

From the above conditions, we note that the steady photon number in one of the two cavities can be zero (in other words, to realize the partially dark optical molecule) by tuning the parameters of the system. Especially, as shown in Fig. 2 when the parameters are set such that $|\lambda_1| = |\lambda_2| = \lambda > 0, \Delta_1 = \Delta_2 = \Delta, \gamma_1 = \gamma_2 = \gamma > 0$, and $J = \sqrt{\Delta^2 + \gamma^2/4}$, we can transfer the dark cavity from cavity 1 to cavity 2 only by adjusting the phase difference adiabatically while keeping the other parameters unchanged, which is available in realistic physical systems.

Here, we emphasize that the two cavities of the optical molecule can not stabilize in their vacuum states simultaneously (i.e., $\alpha_1 = \alpha_2 = 0$). This can be observed from Eqs. (911), which imply $\sin \phi < 0$ when $\alpha_1 = 0$ and $\sin \phi > 0$ when $\alpha_2 = 0$. Thus one can not achieve $\alpha_1 = \alpha_2 = 0$ in this case. Intuitively speaking, this contradiction may be expected to disappear in the system with balanced loss and gain in which $\gamma_1 = -\gamma_2 > 0$. However, further calculation shows det$(M) = 0$ in such a situation if Eqs. (912) are satisfied. That means there does not exist the steady state in the system. In what follows, we will just consider the damping case with $\gamma_1 = \gamma_2 = \gamma > 0$.

IV. PARTIALLY DARK OPTICAL MOLECULE WITH ATOMIC ENSEMBLE

Based on the above discussions about the realization of partially dark optical molecule in the last section, here we continue to study the effects of atom-cavity interaction in the system. To this end, we now consider an ensemble of $N$ identical two-level atoms trapped in cavity 1 as shown in Fig. 3.

In the rotating frame with respect to the frequency $\omega_d$ of the driving field, the Hamiltonian under consideration reads

$$\mathcal{H}' = \Delta_1 a_1^\dagger a_1 + \Delta_2 a_2^\dagger a_2 + \frac{\Delta_b}{2} \sum_i \sigma_z^{(i)}$$

$$+ g \sum_i (a_1^\dagger \sigma_-^{(i)} + a_1 \sigma_+^{(i)}) + J(a_1^\dagger a_2 + a_2^\dagger a_1)$$

$$+ |\lambda_1|(a_1^\dagger e^{-i\phi} + a_1 e^{i\phi}) + |\lambda_2|(a_2^\dagger + a_2), \quad (13)$$
where $\Delta_b = \omega_0 - \omega_d$ with $\omega_0$ the energy level spacing between the ground state $|g\rangle$ and excited state $|e\rangle$ of the two-level atoms, $g$ is the coupling strength between single atom and cavity mode 1. $\sigma^{(i)}_\alpha = |e\rangle \langle i | - |g\rangle \langle i |$ and $\sigma^{(i)}_\beta = [\sigma^{(i)}_\alpha]^\dagger = |e\rangle \langle i |$ are the Pauli operators for the $i$-th atom.

To simplify the above Hamiltonian, we introduce the collective operators for the atomic ensemble,

$$b = \frac{1}{\sqrt{N}} \sum_i \sigma^{(i)}_-, b^\dagger = \frac{1}{\sqrt{N}} \sum_i \sigma^{(i)}_+. \quad (14)$$

In the low-excitation limit with large $N$, the above operators satisfy the standard commutation relation of the bosonic operators

$$[b, b^\dagger] \approx 1. \quad (15)$$

Furthermore, we also have

$$\sum_i \sigma^{(i)}_\alpha = 2b^\dagger b - N. \quad (16)$$

In terms of the collective operators $b$ and $b^\dagger$, the Hamiltonian can be written as

$$\mathcal{H}' = \Delta_1 a_1^\dagger a_1 + \Delta_2 a_2^\dagger a_2 + \Delta_b b^\dagger b + (J a_1^\dagger a_2 + n a b^\dagger b + \lambda |a_1 e^{i\phi} + |a_2 + \text{H.c.}), \quad (17)$$

where $n = g\sqrt{N}$ is the collective coupling strength between the atomic ensemble and cavity mode 1. Here, we have neglected the constant term $-N\Delta_b/2$.

Based on the above Hamiltonian, the Heisenberg-Langevin equation of the system can be written as

$$\dot{A}' = M' A' + B',$$

where $A' = (a_1, a_2, b)^T$, $B' = -i(\lambda_2 |e^{-i\phi} - |a_2, 0)^T$, and

$$M' = \begin{pmatrix}
-i\Delta_1 + \frac{\gamma_b}{2} & -iJ & -i\eta \\
-iJ & -i(\Delta_2 + \frac{\gamma_b}{2}) & 0 \\
-i\eta & 0 & -(i\Delta_b + \frac{\gamma_b}{2})
\end{pmatrix}$$

with $\gamma_b$ the decay rate for the atomic ensemble.

The steady state values of the operators are obtained as

$$\alpha'_1 = \langle a_1 \rangle' = \frac{e^{-i\phi} (i\Delta_b + \frac{\gamma_b}{2}) (R_1 + iI_1)}{-\det(M')}, \quad (20a)$$

$$\alpha'_2 = \langle a_2 \rangle' = \frac{(i\Delta_b + \frac{\gamma_b}{2}) (R_2 + iI_2) + i\lambda_2 \eta^2}{-\det(M')}, \quad (20b)$$

$$\beta' = \langle b \rangle' = \frac{i\eta}{i\Delta_b + \frac{\gamma_b}{2}} \alpha'_1. \quad (20c)$$

Here the superscript "\'" denotes the case with atoms.

From the results given by Eq. (20), we observe the following three points. First, the condition for vacuum steady state in cavity 1 is not changed whenever the atomic ensemble couples or does not couple with the cavity mode by comparing Eq. (20a) with Eq. (5). Second, as shown in Eqs. (20a,20c), when the cavity 1 is in the vacuum state ($\alpha'_1 = 0$), it will not excite the atomic ensemble coupling with it, that is $\beta' = 0$. Third, the condition for the cavity mode 2 achieving its vacuum steady state ($\alpha'_2 = 0$) is modified due to the coupling between the atomic ensemble and cavity mode 1 [As shown in Eq. (12) and Eq. (20b)]. A direct calculation shows that, when $\alpha'_2 = 0$, we need

$$\cos \phi = \frac{\Delta_1 |\lambda_2| (\Delta_b^2 + \gamma_b^2/4) - \Delta_b |\lambda_2| \eta^2}{J |\lambda_1| (\Delta_b^2 + \gamma_b^2/4)}, \quad (21a)$$

$$\sin \phi = \frac{|\lambda_2| \gamma_1 (\Delta_b^2 + \gamma_b^2/4) + \gamma_b |\lambda_2| \eta^2}{2 J |\lambda_1| (\Delta_b^2 + \gamma_b^2/4)}, \quad (21b)$$

which imply

$$\left[ \Delta_1 - \frac{\Delta_b \eta^2}{(\Delta_b^2 + \gamma_b^2/4)} \right]^2 + \left[ \gamma_1 + \frac{\gamma_b \eta^2}{2(\Delta_b^2 + \gamma_b^2/4)} \right]^2 = \frac{J^2 |\lambda_1|^2}{|\lambda_2|^2}. \quad (22)$$

Similar to the situation without atoms, in the situation with atoms we can also transfer the dark cavity from one cavity to the other by only tuning the phase difference between the two driving fields $\phi$. The parameters are set as $\gamma_1 = \gamma_2 = \gamma_3 = \gamma, \Delta_1 = \Delta_2 = \Delta_3 = \gamma, \lambda_1 = \lambda_2 = 0.1 \gamma, g = \sqrt{\gamma^2/2}, \eta = \sqrt{\gamma^2/2}$. Under these parameters, the conditions in Eqs. (10,22) are both satisfied.

FIG. 4: (Color online) The average photons number in cavity 1 ($|\alpha'_1|^2$), cavity 2 ($|\alpha'_2|^2$) and the excitation of the atomic ensemble ($|\beta'|^2$) as functions of the phase difference of the two driving fields $\phi$. The parameters are set as $\gamma_1 = \gamma_2 = \gamma_3 = \gamma, \Delta_1 = \Delta_2 = \Delta_3 = \gamma, \lambda_1 = \lambda_2 = 0.1 \gamma, g = \sqrt{\gamma^2/2}, \eta = \sqrt{\gamma^2/2}$. Under these parameters, the conditions in Eqs. (10,22) are both satisfied.

\[ J = \sqrt{\Delta^2 + \gamma^2/4}, \eta = \sqrt{2(\Delta^2 - \gamma^2/4)}. \]
Under these conditions, we plot the average photon numbers in the two cavities and the excitation number of the atomic ensemble as functions of the phase difference $\phi$ between the two driving fields in Fig. 4 with the parameters setting as $|\alpha_1| = |\alpha_2| = \lambda = 0.1\gamma$, $\Delta_1 = \Delta_2 = \Delta_0 = \Delta = \gamma$, $g = \sqrt{\gamma}/2$, and $\eta = \sqrt{\eta}/2$. As shown in this figure, when $\phi = -0.14\pi$ [$= \arcsin(-1/\sqrt{5})$], the cavity mode 1 achieves the vacuum steady state, and the atomic ensemble will not be excited ($|\alpha_1|^2 = |\beta|^2 = 0$). On the other hand, when $\phi$ is tuned to $\phi = 0.557\pi$ [$= \arccos(-0.08\sqrt{5})$], the cavity mode 2 can be stabilized in its vacuum state ($|\alpha_2|^2 = 0$), while the cavity mode 1 and atomic ensemble are excited.

V. CONCLUSION

In summary, we have shown the scheme to realize the partially dark optical molecule via only tuning the phase difference between the two driving fields. The fact that the average photon numbers of the cavities in the optical molecule are significantly dependent on the phase difference results from the quantum interference effect happening in the colosed energy level diagram. We analytically give the conditions to realize the partially dark molecule (that is one of the cavity modes achieves its vacuum steady state). Moreover, when an additional ensemble of two-level atoms is coupled with one of the cavities (e.g. cavity 1), analytical calculation showed that the optical molecule can be still partially dark. In both of the situations when the atomic ensemble is present or absent, we find that the dark cavity can be transferred from one cavity to the other only by adjusting the phase difference while keeping other parameters remained. Compared with the case without atoms, the condition for cavity 1 being dark is unchanged and that for cavity 2 being dark is modified in the case with atoms. It is interesting that when the cavity 1 is dark, the atomic ensemble inside cavity 1 will also be dark with 0 excitation number. That means the cavity as well as the atoms inside it can be “shielded” in the optical molecule even at the present of the optical drivings. Our scheme for phase control in optical molecules might provide a platform for applications on quantum information process based on photonic devices.

Acknowledgments

This work is supported by the National Basic Research Program of China (under Grants No. 2014CB921403 and No. 2016YFA0301200), NSFC (under Grants No. 11404021 and No. U1530401), and the Fundamental Research Funds for the Central Universities (under Grant No. 2412016KJ015).

[1] K. J. Vahala, Nature (London) 424, 839 (2003).
[2] H. J. Kimble, Nature (London) 453, 1023 (2008).
[3] L. Zhou, Z. R. Gong, Y. X. Liu, C. P. Sun, Phys. Rev. Lett. 101, 100501 (2008).
[4] L. Zhou, L. P. Yang, Y. Li, and C. P. Sun, Phys. Rev. Lett. 111, 103604 (2013).
[5] K. Xia and J. Twamley, Phys. Rev. X 3, 031013 (2013).
[6] T. Tian, D. Xu, T.-Y. Zheng, and C. P. Sun, Eur. Phys. J. D 67, 69 (2013).
[7] A. D. Greentree, C. Tanhan, J. H. Cole, and L. C. L. Hollenberg, Nat. Phys. 2, 856 (2006).
[8] J. Koch and K. L. Hur, Phys. Rev. A 80, 023811 (2009).
[9] C. D. Ogden, E. K. Irish, and M. S. Kim, Phys. Rev. A 78, 063805 (2008).
[10] M. Bayer, T. Gutbrod, J. P. Reithmaier, A. Forchel, T. L. Reinecke, P. A. Knipp, A. A. Dremin, and V. D. Kulakovskii, Phys. Rev. Lett. 81, 2582 (1998).
[11] Y. P. Rakovich and J. F. Donegan, Laser Photon. Rev. 4, 179 (2010).
[12] X.-W. Xu and Y. Li, Phys. Rev. A 90, 043822 (2014); ibid. 90, 033809 (2014).
[13] H. Z. Shen, Y. H. Zhou, and X. X. Yi, Phys. Rev. A 90, 023849 (2014).
[14] J. Li, R. Yu, and Y. Wu, Phys. Rev. A 92, 053837 (2015).
[15] F. Nissen, S. Schmidt, M. Biondi, G. Blatter, H. E. Tureci, and J. Keeling, Phys. Rev. Lett. 108, 233603 (2012).
[16] Y.-C. Liu, X. Luan, H.-K. Li, Q. Gong, C. W. Wong, and Y.-F. Xiao, Phys. Rev. Lett. 112, 213602 (2014).
[17] L. Chang, X. Jiang, S. Hua, C. Yang, J. Wen, L. Jiang, G. Li, G. Wang, and M. Xiao, Nat. Photon. 8, 524 (2014).
[18] B. Peng, S. K. Ozdemir, F. Lei, F. Monifi, M. Gianfreda, G. L. Long, S. Fan, F. Nori, C. M. Bender, and L. Yang, Nat. Phys. 10, 394 (2014).
[19] C. P. Sun, Y. Li, and X. F. Liu, Phys. Rev. Lett. 91, 147903 (2003); G. R. Jin, P. Zhang, Y. X. Liu, and C. P. Sun, Phys. Rev. B 68, 134301 (2003).
[20] Y.-X. Liu, J. Q. You, L. F. Wei, C. P. Sun, and F. Nori, Phys. Rev. Lett. 95, 087001 (2005).
[21] W. Z. Jia and L. F. Wei, Phys. Rev. A 82, 013808 (2010).
[22] M. Shapiro, E. Frishman, and P. Brumer, Phys. Rev. Lett. 84, 1669 (2000); P. Král and M. Shapiro, Phys. Rev. Lett. 87, 183002 (2001); P. Král et al., Phys. Rev. Lett. 90, 033001 (2003).
[23] Y. Li, C. Bruder, and C. P. Sun, Phys. Rev. Lett. 99, 130403 (2007).
[24] J. Tang, W. Geng, and X. Xu, Sci. Rep. 5, 9252 (2015).
[25] W. Z. Jia, L. F. Wei, Y. Li, and Y.-x. Liu, Phys. Rev. A 91, 043843 (2015).
[26] X. W. Xu and Y. J. Li, J. Phys. B: At. Mol. Opt. Phys. 46, 035502 (2013).