Spatially Separated and Correlated Atom-molecule Lasers from a Bose Condensate

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We propose a feasible scheme to create two spatially separated atomic and molecular beams from an atomic Bose-Einstein condensate by combining the Raman-type atom laser output and the two-color photo-association processes. We examine the quantum dynamics and statistical properties of the system under short-time limits, especially the quadrature-squeezed and mode-correlated behaviors of two output beams for different initial state of the condensate. The possibility to generate the entangled atom-molecule lasers by an optical technique was also discussed.

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The experimental realizations of Bose-Einstein condensates (BEC) in cold dilute atomic gases have provided a rich playground to manipulate and demonstrate various properties of quantum degenerate gases [1]. Recently rapid advances have been witnessed for creating a quantum degenerate molecular gas via a magnetic Feshbach resonance [2-3] or an optical photo-association (PA) [4-5] in an atomic BEC, and the appealing physical properties of the formed atom-molecule mixtures were investigated very extensively under the quasi-homogeneous trapping conditions [2-5]. The technique of coherent PA not only produces a new species of BEC but also leads to many interesting quantum statistical effects due to its nonlinear coupling nature in the dynamics [6]. The possible applications of a molecular condensate are expected in, e.g., the precise matter-wave interferometry technique [7].

On the other hand, there always have been many interests in creating an atom laser and exploring its novel properties, since the MIT-group first realized a pulsed atom laser by using quantum state transfer technique [8]. Successive experimental achievements in the design and amplification of atom laser were obtained and stimulated amounts of theoretical works in both the output coupling and the properties of atom laser [9]. As the matter-wave analogy of an optical laser, the atom or molecule lasers now are expected to have some important applications in practice [7, 9]. Among the constantly expanding catalogue of atom laser schemes, the technique of Raman output coupling was extensively studied in order to obtain a continuous atomic beam with adjustable momentum [10]. For a propagating atom laser, one also can further study its manipulations such as the atomic filamentation and correlation for a travelling beam across a magnetic Feshbach resonance region [11].

A natural question, then, may arise: is it possible to create two spatially separated and correlated atomic and molecular beams from one trapped atomic condensate by combining the above two techniques? The main purpose of this paper is to study this interesting problem, focusing on the role of coherent two-color PA process in the Raman atom laser coupler. We will show that, for the classical input and control lights, the five-level atom-molecule system can be adiabatically reduced into an effective three-state one. And, by probing the quantum dynamics and statistical properties of the system under short-time limits, we can observe the quadrature-squeezed and mode-correlated behaviors of two output beams which depends on different initial state of the condensate. For the quantized input lights, we also briefly discussed the possibility to generate the entangled atom-molecule beams by applying two entangled lights.

Turning to the situation of Fig. 1, we assume for simplicity that large number of Bose-condensed atoms are initially prepared in the $c$ state when two strong control lights with Rabi frequency $\Omega_i$ ($i=1, 2$) are applied. The atomic coupling $|c\rangle \rightarrow |e\rangle$ and the photo-association (PA) $|c\rangle \rightarrow |m\rangle$ processes are described by two input lights with frequency $\varepsilon_i$ ($i=1, 2$). Note that the two states $|e\rangle$ and $|m\rangle$ mediate the two kinds of output coupling Raman transitions and then the stable atoms and molecules are created in the spatially separated untrapped modes $|b\rangle$ and $|g\rangle$, respectively. Since the atomic collisions ef-
fects on the dynamics of the system are extensively studied [12-13] and its strength can be tuned by the technique of magnetic-field-induced Feshbach resonance [14-15], hence, to see clearly the role of nonlinear PA interactions in the Raman atom-laser output process, we ignore it for present purpose (the strengths for the molecules or atom-molecule collisions are yet not known [5]).

In the second quantized notation, boson annihilation operators for the three-state atoms and the formed molecules in two states are denoted by $\hat{c}$, $\hat{\bar{c}}$, $\hat{b}$ and $\hat{\bar{m}}$, $\hat{\bar{g}}$, respectively. Thereby, focusing on the different modes couplings, the quantum dynamics of this system can be described by the five-mode Hamiltonian ($\hbar = 1$)

$$\hat{H}_5 = -\delta_1 \hat{c}^\dagger \hat{c} - \delta_2 \hat{\bar{m}}^\dagger \hat{\bar{m}} + \hat{H}_{Li} + \hat{H}_{RI},$$

$$\hat{H}_{Li} = \varepsilon_1 (\hat{c}^\dagger \hat{c} + H.c.) + \Omega\{\hat{b}^\dagger \hat{b} + H.c.\},$$

$$\hat{H}_{RI} = \varepsilon_2 (\hat{\bar{m}}^\dagger \hat{\bar{m}} + H.c.) + \Omega\{\hat{\bar{g}}^\dagger \hat{\bar{g}} + H.c.\},$$

(1)

where $\delta_1$ is the intermediate detunings and the coupling strengths are taken as real numbers. Here, for simplicity, we have ignored the incoherent process of the excited-state molecular damping or the effect of molecular dissociating into those non-condensate atomic modes [16]. In practice, the weak PA field condition $\epsilon \ll \Omega$ could safely avoid any heating effects in the PA process. Obviously there exists a conserved quantity for this dynamical system: $\hat{c}^\dagger \hat{c} + \hat{\bar{m}}^\dagger \hat{\bar{m}} + \hat{\bar{g}}^\dagger \hat{\bar{g}} \equiv N_0$, where $N_0$ is the total atom number for a condensate of all atoms or twice the total molecule numbers.

From this five-mode Hamiltonian $\hat{H}_5$, we can write the Heisenberg equations of motion of the excited atoms and molecules which, by assuming $|\delta_1| (i = 1, 2)$ as the largest evolution parameters [16] in the system or $\hat{c} / \delta_1 = 0$, $\hat{\bar{m}} / \delta_2 = 0$, leads to

$$\dot{\hat{c}} \approx \frac{\varepsilon_1}{\delta_1} \hat{c} + \frac{\Omega\{\hat{b} + H.c.\}}{\delta_1}, \quad \dot{\hat{\bar{m}}} \approx \frac{\varepsilon_2}{\delta_2} \hat{\bar{m}} + \frac{\Omega\{\hat{\bar{g}} + H.c.\}}{\delta_2} \hat{\bar{g}},$$

(2)

Substituting this into Eq. (1), which means adiabatic eliminations of the excited atomic and molecular modes, yields the effective three-mode Hamiltonian

$$\hat{H}_3 = \lambda_1 \hat{b}^\dagger \hat{b} + H.c. + \lambda_2 [\hat{\bar{g}}^\dagger \hat{\bar{g}} + H.c.],$$

(3)

where $\lambda_i = \varepsilon_i \Omega / \delta_i$ (i = 1, 2). The free motion part was ignored since it only appears as the global phases for the output fields and has no effects on our physical results. Also we omitted the small term of effective atomic collisions $(\varepsilon_2 / \delta_2)^2 \varepsilon_1^2 \lambda_2^2$ for the reasons described above. Note that, by applying the mean-field approximation: $(\hat{A} - \langle\hat{A}\rangle)(\hat{B} - \langle\hat{B}\rangle) \approx 0$ or $\hat{A} \hat{B} \sim \langle\hat{A}\rangle\langle\hat{B}\rangle - \langle\hat{A}\rangle\hat{B} + \hat{A}\langle\hat{B}\rangle$, this three-mode Hamiltonian can be reduced into some perturbed from of the well-known linear three-level coupling system [17-21]. The quantum transfer technique based on the linear three-level optics (TLO) has been intensively studied and various transfer processes have been realized, e.g., between different internal atomic or molecular quantum states [18], from light to atomic ensembles or propagating atomic beams [19-20, 13, 21] and vice versa. Thereby the mutual coherence of the two output fields can be intuitively expected in our present system.

Now we use the short-time evolution method to analytically study the quantum dynamics and statistical effects of this system beyond the mean-field approximation. The Heisenberg equations of motion for the trapped condensate, the output atomic and molecular modes read

$$\dot{\hat{c}} = i\lambda_1 \hat{b} + 2it\lambda_2 \hat{\bar{c}}^\dagger \hat{\bar{g}},$$

$$\dot{\hat{\bar{m}}} = i\lambda_1 \hat{c}, \quad \dot{\hat{\bar{g}}} = i\lambda_2 \hat{\bar{c}} \hat{\bar{c}},$$

(4)

respectively. Taking into account of the fact that the loss of atoms from a condensed state occurs in impressively short time scales (up to two hundreds of $\mu$s) [14], we now focus on the short-time behaviors of this dynamical system by readily deriving the solutions in second order of evolution time as $(\delta K(t) \approx K(t) - K_0)$

$$\delta \hat{c}(t) = it\lambda_1 \hat{b}_0 + 2it\lambda_2 \hat{\bar{c}}^\dagger \hat{\bar{g}}_0 - \frac{1}{2} \lambda_2^2 \hat{\bar{c}}^\dagger \hat{\bar{g}}_0 - \lambda_2^2 \hat{\bar{c}}^\dagger \hat{\bar{g}}_0, \quad \delta \hat{\bar{m}}(t) = it\lambda_1 \hat{c}_0 - \frac{1}{2} \lambda_2^2 \hat{\bar{c}}^\dagger \hat{\bar{g}}_0 - \lambda_2^2 \hat{\bar{c}}^\dagger \hat{\bar{g}}_0, \quad \delta \hat{\bar{g}}(t) = - it\lambda_2 \hat{\bar{c}}^\dagger \hat{\bar{g}}_0 + \lambda_2^2 \hat{\bar{c}}^\dagger \hat{\bar{g}}_0 + 1) \hat{\bar{g}}_0.$$

(5)

Obviously, we can get a conserved quantity: $\hat{c}^\dagger \hat{c} + \hat{\bar{b}}^\dagger \hat{\bar{b}} + 2\hat{\bar{g}}^\dagger \hat{\bar{g}} \equiv N_0$, as it should be. Note that the main feature of our present scheme is the creation of two spatially separated atomic and molecular beams from a three-level atomic ensemble, which is quite different from the elegant scheme of creating two entangled atomic beams by spin-exchange interactions from a spinor condensate [22]. In addition, comparing our reduced model to that of the simple two-color PA process studied by, e.g., Calsamiglia et al. [16], we note that these two three-mode models are formally similar, but again essentially different.

Using the solutions obtained above, one can easily study the interested quantum statistical properties for the output atoms and molecules. As a concrete example, here we analyze the different quantum squeezing behaviors in this system and we would see that in the short-time limits, unlike the usual PA case, the output molecules can exhibit an interesting squeezing-free property even in the presence of the nonlinear atom-molecule coupling within the propagating beam; however, if the trapped condensate is initially prepared in a squeezed state, the output atoms and molecules may also show the quadrature squeezed effects, indicating a possible control of quantum statistics of the output particles by steering the quantum state of input atomic condensate.

Firstly, we assume a coherently factorized initial state of the system, i.e., $|\alpha\rangle = |0\rangle |\alpha\rangle$ with $\hat{c}(\alpha) = |\alpha| e^{i\varphi}$. Taking into account of the quadrature squeezed coefficients defined by [23]

$$S_i = \frac{\langle \Delta \hat{G}_i \rangle^2 > - \frac{1}{2} | \langle \hat{G}_1, \hat{G}_2 \rangle > \frac{1}{2} | \langle \hat{G}_1, \hat{G}_2 \rangle |}{\frac{1}{2} | \langle \hat{G}_1, \hat{G}_2 \rangle |}, \quad i = 1, 2$$

(6)
where \( \hat{G}_1 = \frac{1}{2} (\hat{g} + \hat{g}^\dagger) \), \( \hat{G}_2 = \frac{1}{2} (\hat{g} - \hat{g}^\dagger) \), then we can get the results for the output atomic and molecular modes

\[
\begin{pmatrix}
S_{1a}(t) \\
S_{2a}(t)
\end{pmatrix} = \frac{3}{4} \alpha^2 \lambda_2^2 \left( \frac{\sin^2 \varphi}{\cos^2 \varphi} \right) > 0,
\]

and

\[
\begin{pmatrix}
S_{1b}(t) \\
S_{2b}(t)
\end{pmatrix} = \frac{1}{4} \alpha^4 \lambda_2^2 \left( \frac{\sin^2 2\varphi}{\cos^2 2\varphi} \right) > 0,
\]

respectively. This means that there is still no squeezing for these two modes even beyond the atomic depleted approximation. It can be readily verified that, however, for the trapped atoms this time-independent no-squeezing effect happens only for the case of \(|\cos \varphi| = |\sin \varphi|\); for the general cases, it really can exhibit the dynamical quadrature-squeezing behaviors.

Secondly, let us consider an initially squeezed atomic condensate (generated by, e.g., the binary Kerr-type collisions [13]) described by [24]: \(|\alpha \rangle = \hat{S} (\xi) |\alpha \rangle \), where the squeezed operator \( \hat{S} (\xi) = \exp [\xi (\hat{c}^\dagger - \hat{c}^\dagger \hat{c})] \) with \( \xi = \frac{\lambda_2}{2} e^{i \varphi} \), as a unitary transformation on the Glauber coherent state \(|\alpha \rangle \equiv |\alpha \rangle e^{i \varphi} \). Here \( r \) and \( \phi_s \) denote the squeezed strength and angle, respectively. For simplicity, we only consider the case of squeezed vacuum state for input atoms, then for the two output beams we can get an interesting result for the particles flux

\[
\langle N_s (t) \rangle_s = \eta (1 + 3 \sin^2 r) \langle N_b (t) \rangle_s,
\]

with \( \eta \equiv (\lambda_2 / \lambda_1)^2 \). This indicates a feature of two-mode correlation for this system, which is somewhat similar to the case of linearly coupling three-state system [18] or even the scheme of spinor condensate output coupler [22]. It is clear that the relative flux ratio is completely determined by the coupling-strength ratio \( \eta \) and the squeezed degree \( r \). For example, if we take the equal coupling strengths or \( \eta = 1 \), we have \( \tilde{N}_g > \tilde{N}_b \), i.e., the molecular beam looks brighter than the atomic beam \((r > 0)\) and, more squeezing, much brighter! For possible applications, this may provide a feasible way to measure the atomic squeezing degree of the trapped condensate just by comparing the counted particles flux of two output beams.

As a further illustration, we study the quantum statistical properties of these two output beams. It is readily to show that, the Mandel’s Q parameters [24] for the output atomic and molecular fields

\[
Q^a_{b,g}(\tau) = \frac{\langle \Delta \tilde{N}^2_s (\tau) \rangle_s}{\langle N_s (\tau) \rangle_s} - 1 < 0,
\]

which means that, at least in short-time limits, the two output beams both satisfy the sub-Poisson distribution. It should be remarked that the atomic depletion effect of trapped condensate plays a key role in these results. In fact, if one makes the Bogoliubov or undepleted approximation, the three-mode Hamiltonian Eq. (3) becomes nothing but a trivial uncorrelated two-mode model.

In addition, we also can derive the squeezed coefficients for the output atomic filed, i.e.,

\[
S^c_{1b,2b}(t) = 2 \lambda_1^2 t^2 \sinh (\sinh r \pm \cosh r \cos \phi_s),
\]

and similarly, for the output molecules we have

\[
\begin{pmatrix}
S^c_{1g}(\tau) \\
S^c_{2g}(\tau)
\end{pmatrix} = \tau^2 \left[ 11 (\sinh^2 r + 1) \left( \frac{\cos^2 \phi_s}{\sin^2 \phi_s} \right) - 4 \right],
\]

where \( \tau \equiv \lambda_2 t \sinh r \). Clearly these simple results indicate an interesting squeezed-angle-dependent squeezing effect \((r > 0)\): (i) for \( \phi_s = 2n\pi \ (n = 0, 1, 2, \ldots) \), we have \( S_{1b} = \lambda_1^2 t^2 (e^{2r} - 1) > 0 \) and \( S_{2b} = \lambda_1^2 t^2 (e^{-2r} - 1) < 0 \), which means that the quadrature component \( S_{2b} \) is squeezed; (ii) but for \( \phi_s = (2n + 1)\pi \), we have \( S_{1b} = S_{2b} (\phi_1 = 2n\pi) < 0 \) and \( S_{2b} = S_{1b} (\phi_1 = 2n\pi) > 0 \), i.e., the squeezing effect now transfers to \( S_{1b} \) component; one should note that, for these two cases, the output molecular field is also squeezed (both for the component \( S_{2b} \); (iii) for \( \phi_1 = (n + 1/2)\pi \), it can be easily seen that the output atomic beam is never squeezed, but the molecular beam is still squeezed (but for the component \( S_{1b} \)); (iv) but for \( \phi_1 = (n + 1/4)\pi \), we can see that the molecular beam is never squeezed but the atomic beam really can exhibit the squeezing effect if the squeezed strength satisfies: \( r < \ln(1 + \sqrt{2}) \approx 0.88 \). Therefore, by controlling the squeezed parameters of initial atomic field, one can realize the quantum squeezing in either of the output atomic or molecular beam, or in both of them!

Finally we would like to make some remarks about the mutual coherence of the output atomic and molecular fields which can be best characterized by the second-order cross-correlation function

\[
g_{bg}^{(2)}(t) = \frac{\langle \hat{b}^\dagger (t) \hat{b} (t) \hat{g}^\dagger (t) \hat{g} (t) \rangle}{\langle \hat{b}^\dagger (t) \hat{b} (t) \rangle \langle \hat{g}^\dagger (t) \hat{g} (t) \rangle}.
\]

It is easily verified that, however, one should write the solutions of Eq. (4) at least in fourth order of time to determine the results \( g_{bg}^{(2)}(t) < 1 \) (anti-correlated states). This means that the correlations between the two output modes are dynamically established due to the depletion of trapped atoms. Therefore, one would ask the question about the possibility of generating quantum correlations or entanglement between the output atoms and molecules under the limits of large condensed atoms.

We note that, our present scheme really can realize this task if one takes the two input lights (including the \(|\epsilon \rangle \rightarrow |\epsilon \rangle \) coupling light and the PA light) as quantized fields (denoted by \( \hat{a}_{1,2} \)), after the replacement of \( \epsilon, \hat{c}^\dagger \rightarrow N_0 \) and the adiabatic approaches like Eq. (2), the totally seven-mode Hamiltonian can be reduced to a simple linearly coupling four-mode one, i.e. [13]

\[
\hat{H}_4 = \lambda_1 \left[ \hat{b}^\dagger \hat{a}_1 + H.c.] + \lambda_2 [\hat{g}^\dagger \hat{a}_2 + H.c.] \right],
\]

where \( \lambda_i = \lambda_i \sqrt{N_0} \ (i = 1, 2) \). Obviously, this simple form determines a factorized structure of wave function
of the system [13, 25], especially the property of perfect quantum conversion : $\hat{a}_1 \rightarrow \hat{b}$, $\hat{a}_2 \rightarrow \hat{g}$ [13]. Therefore, by preparing two entangled input lights, one can create two spatially separated and entangled atomic and molecular beams, which indicates a simple but interesting optical technique for quantum control of the output atom-molecule beams. As a concrete example, if we prepared the input lights in a two-mode squeezed vacuum state, i.e., $|\psi\rangle = \exp\left(\zeta \hat{a}_1^\dagger \hat{a}_2 - \zeta^* \hat{a}_1 \hat{a}_2\right) |0\rangle$, with the squeezed parameter $\zeta = \kappa e^{-i\phi}$, it is straightforward to show that, for the simplest case $\lambda = \lambda' = \lambda$, we have $g_{bg}^{(2)}(t) = 2 + \sinh^2 \kappa > 1$ (correlated state). This is different form the atom-molecule correlations due to the atomic depletions. Also, it turns out that for the two output modes: $|g_{bg}^{(2)}(t)|^2 > |g_b^{(2)}(t)|g_g^{(2)}(t)$, i.e., there is violations of the Cauchy-Schwarz inequality (CSI) for them, which, according to Reid and Walls [24], can be accompanied by violations of Bells inequality (nonlocality).

In conclusion, we have proposed a feasible scheme to create two spatially separated and correlated atomic and molecular beams from one trapped three-level atomic Bose-Einstein condensate, by studying the role of two-color coherent photo-association process in the Raman-type atom laser out coupler. We examine the quantum dynamics and statistical properties of the output atomic and molecular fields under short-time limits, especially the quadrature squeezed effects and mode-correlated behaviors of the atom-molecule beams, for different prepared states of the trapped atomic condensate. The simple but accessible way to generate the entangled atom-molecule lasers from a very large condensate by an optical technique (weak input lights) was also discussed.

Of course, even more intriguing subjects can exist in the extensive studies of this simple scheme. For example, the effects of particles collisions in propagating modes should be considered in further analysis although these terms can be tuned in trapped regime by, e.g., the magnetically-induced Feshbach resonance technique. As our earlier work on this problem within the context of an atom laser out-coupling [13] shows, the squeezed effects also can be predicted for the output molecules due to intrinsic collisions. And, for the quantized input lights, especially a quantized PA light [26], the atomic depletions effect and the quantum noise terms should be studied by, e.g., the standard numerical method based on $\epsilon$-number stochastic equations in positive-$P$ representation of quantum optics [5,6]. Our investigations here provides the possibilities for these appealing researches.

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