Collision-assisted electromagnetically induced control of coherent population transfer

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The effect of the collisions on the control of coherent population transfer in a closed inverse *Y*-type four-level system driven by three laser fields is investigated with the stimulated Raman adiabatic passage technique. An arbitrary coherent superposition between the initial state and target state can be created either by varying the Rabi frequency of the control laser field or by tuning the one-photon detunings of the pump and Stokes laser fields. When the three laser fields with nearly equal peak Rabi frequencies are each tuned to resonance with the respective transitions, the low transfer efficiency due to the nonadiabatic coupling between two degenerate adiabatic states could be enhanced dramatically with the increase of the collision-induced coherence decay rates to the value nearly comparable to the Rabi frequency of the control field. The enhanced transfer efficiency results from the collision-controlled electromagnetically induced transparency in the Λ-type three-level subsystem and electromagnetically induced absorption in the ladder-type three-level subsystem of the four-level system.

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I. INTRODUCTION

The electromagnetic-field-driven atomic or molecular system may exhibit many effects, such as spontaneous emission cancellation [1,2], coherent population trapping (CPT) [3], electromagnetically induced transparency (EIT) [4], laser without inversion [5], strong narrowing of spectral line [6], and rapid adiabatic population transfer [7]. The underlying physical mechanism of these effects is quantum coherence and interference. Quantum interference can exhibit either a constructive or destructive feature, which critically depends not only on the atomic or molecular structures and parameters, but also on the experimental conditions, such as the collisions and laser field polarization. Zhu showed that the nature of spontaneous emission interference depends on the alignment of the two dipole moments for the two relative transitions, and the destructive quantum interference can lead to the cancellation of spontaneous emission [1,2]. Agarwal [8] pointed out that, in optically driven *V*-type, Λ-type, and ladder-type three-level systems, whether electromagnetically induced absorption (EIA) or EIT due to constructive or destructive interference depends on the excitation scheme, and the dephasing collisions can even change the nature of the interference. The laser field polarization dependence of the interference has been experimentally studied in two-color two-photon polarization spectroscopy [9]. Recently, we have experimentally and theoretically studied the collision-induced constructive and destructive quantum interferences in both the frequency and time domains [10]. In this paper, in contrast to the previous studies [11,12] that the dephasing collisions are detrimental to coherent population transfer in the Λ-type three-level system, we show that coherent population transfer can be significantly enhanced via the collision-controlled EIT in the Λ-type three-level subsystem and EIA in the ladder-type three-level subsystem in a closed inverse *Y*-type four-level system driven by three laser fields with the stimulated Raman adiabatic passage (STIRAP) technique under certain conditions.

Coherently controlling population transfer from an initial state to a target state and creating an arbitrary superposition between them has attracted considerable interest in recent years due to its extensive applications to control of chemical reaction, collision dynamics, quantum information processing, and atomic optics [7]. The STIRAP has proven to be an efficient and robust technique for selective and complete coherent population transfer and creating an arbitrary superposition between two discrete atomic or molecular states [7]. As is well known, in the simplest Λ-type three-level system, the system would evolve solely along the dark state composed only of the two lower states 1 and 3 at all times, and perfect population transfer from the initially populated state 1 to target state 3 without ever actually populating the intermediate state 2 can be realized with the counterintuitively ordered pump and Stokes pulses in the adiabatic regime. Apart from the Λ-type three-level system, the tripod-type four-level system has also been extensively studied theoretically [13] and experimentally [14]. In the case of controlling population transfer and creating a coherent superposition state, the present inverse *Y*-type four-level system driven by three laser fields has a similar feature to the driven tripod-type four-level system studied in Refs. [13,14] without the consideration of the population relaxation and phase relaxation. However, when the dephasing collisions are taken into account, we demonstrate that the low transfer efficiency due to the nonadiabatic coupling between two degenerate adiabatic states could be enhanced dramatically with increasing the collision-induced coherence decay rates in a moderate range when the three laser fields with nearly equal peak Rabi frequencies are each tuned to resonance with the respective transitions, whereas the collisions nearly have no effect on the transfer efficiency in the tripod-type four-level system.

The organization of the paper is as follows. In Sec. II, we analyze the evolution of population transfer in the closed inverse *Y*-type four-level system driven by three laser fields

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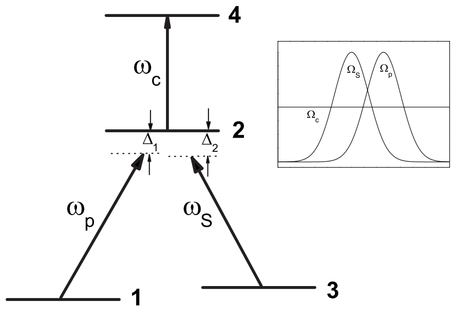

FIG. 1. The closed inverse Y-type four-level system driven by three laser fields shown in the inset.

in the adiabatic representation. In Sec. III, we present the numerical results about the enhanced population transfer via the collision-controlled EIT in one subsystem and EIA in another subsystem by solving the time dependent density matrix equation. Finally, we summarize the main results in Sec. IV.

II. ADIABATIC EVOLUTION OF THE SYSTEM

The inverse Y-type four-level system driven by three laser fields is shown in Fig. 1, and the inset shows the three laser fields. States 1, 2, and 3 form the standard Λ-type three-level system driven by the pump and Stokes pulses with the Rabi frequencies $\Omega_p(t)=\mu_1 E_p(t)/\hbar$ and $\Omega_S(t)=\mu_2 E_S(t)/\hbar$, respectively, where μ_1 (or μ_2) is the dipole moment for the transition 1-2 (or 3-2), and $E_p(t)$ and $E_S(t)$ are the envelopes of the electric-field amplitudes. States 2 and 4 are coupled by the control laser field with a constant Rabi frequency $\Omega_c=\mu_3 E_c/\hbar$. The Rabi frequencies of the pump and Stokes pulses are assumed Gaussian with the amplitude envelopes of the form $\Omega_p(t)=\Omega_p \exp[-(t-\tau)^2/T^2]$ and $\Omega_S(t)=\Omega_S\exp(-t^2/T^2)$, respectively, where T is the pulse duration, Ω_p and Ω_S are the peak values of the Rabi frequencies of the two pulses, and τ is the time delay between them. The detunings of the pump and Stokes lasers from the resonant transitions 1-2 and 3-2 are $\Delta_1=\omega_p-\omega_{21}$ and $\Delta_2=\omega_S-\omega_{23}$, respectively, where ω_{ij} $(i\neq j)$ is the resonant frequency between levels i and j, and ω_p and ω_S are the pump and Stokes laser frequencies. For simplicity, we assume that the two-photon resonance between levels 1 and 3 is maintained (we denote $\Delta=\Delta_1=\Delta_2$) and the control laser field is tuned to the resonant transition 2-4. In the rotating-wave approximation, the time-dependent Hamiltonian of the atom-field system can be written as

$$H=\hbar\begin{pmatrix} 0 & \Omega_p(t) & 0 & 0 \\ \Omega_p(t) & -\Delta & \Omega_S(t) & \Omega_c \\ 0 & \Omega_S(t) & 0 & 0 \\ 0 & \Omega_c & 0 & -\Delta \end{pmatrix}. \tag{1}$$

In the adiabatic limit, it is convenient to study the time evolution of the system in the adiabatic representation. As analyzed in Ref. [13], when the three laser fields are each tuned to resonance with the respective transitions, there exist two degenerate eigenstates (adiabatic states) of the Hamiltonian with the eigenvalues being zero, which are

$$|\phi_0\rangle=\cos\theta|1\rangle-\sin\theta|3\rangle, \tag{2}$$

$$|\phi_1\rangle=\sin\theta\sin\varphi|1\rangle+\cos\theta\sin\varphi|3\rangle-\cos\varphi|4\rangle, \tag{3}$$

where $\tan\theta=\Omega_p(t)/\Omega_S(t)$ and $\tan\varphi=\Omega_c/\sqrt{\Omega_p^2(t)+\Omega_S^2(t)}$. When the control laser field is absent, the inverse Y-type four-level system turns into the extensively studied Λ-type three-level system for the STIRAP, and in the adiabatic regime the system would evolve solely along the dark state φ_0 and complete population transfer from state 1 to state 3 can be obtained with the counterintuitively ordered pump and Stokes pulses. In the presence of the control laser field, the system dressed by the control field is equivalent to the double Λ-type four-level system studied in Refs. [2,15] with the energy separation of the upper doublet equal to $2\Omega_c$. In this case, although the initially populated state 1 coincides with the dark state φ_0, the system would not evolve solely along this dark state, as there exists a nonadiabatic coupling between the degenerate adiabatic states φ_0 and φ_1. Consequently, the outcome state $\Psi(\infty)$ of the system is a mixture of the two bare states 1 and 3, which can be described as

$$|\Psi(\infty)\rangle=\sin\gamma_f(\infty)|1\rangle-\cos\gamma_f(\infty)|3\rangle, \tag{4}$$

where $\gamma_f(t)=\int_{-\infty}^{t} d\theta/dt' \sin\varphi dt'$ is the Berry phase [13]. It can be seen from Eq. (4) that, if $\Omega_c\ll\Omega_p$ (Ω_S), $\gamma_f(\infty)$ is nearly equal to zero, and almost perfect population transfer can be realized; if $\Omega_c\gg\Omega_p$ (Ω_S), $\gamma_f(\infty)$ nearly equals $\pi/2$, and nearly no population transfer can take place. However, when Ω_c is comparable to Ω_p or Ω_S, only a part of the populations can be transferred from state 1 to state 3, and a coherent superposition between them is established.

The above analysis can be seen clearly from the final populations in the four states as a function of the one-photon detunings of the pump and Stokes lasers under different Rabi frequency Ω_c of the control field by numerically solving the time-dependent Schrödinger equation, as shown in Fig. 2. When the control field is absent, the transfer efficiency approaches 100% and shows a weak dependence on the one-photon detunings of the two pulses due to the adiabaticity [see Fig. 2(a)]. With the increase of the Rabi frequency Ω_c, the population in state 3 appears as a narrow dip at the one-photon resonances of the two pulses due to the nonadiabatic coupling between φ_0 and φ_1. A further increase of the Rabi frequency Ω_c would lead to larger depth and width of the dip. When the Rabi frequency Ω_c is about 2.5 times as large as the Rabi frequencies Ω_p and Ω_S, nearly no population transfer can take place at the one-photon resonances of the two pulses, as displayed in Fig. 2(d). It can be seen from Fig. 2 that an arbitrary coherent superposition between the initial state 1 and target state 3 can be created either by varying the Rabi frequency of the control field with the three laser fields each tuned to resonance with the respective transitions or by tuning the one-photon detunings of the pump and Stokes laser fields with a sufficiently strong control field. When the Rabi frequencies Ω_c, Ω_p, and Ω_S are nearly equal to each other, only a part of the populations can be transferred from state 1 to state 3 due to the nonadiabatic coupling between φ_0 and φ_1. Without the consideration of the population relaxation and phase relaxation, the present inverse Y-type four-

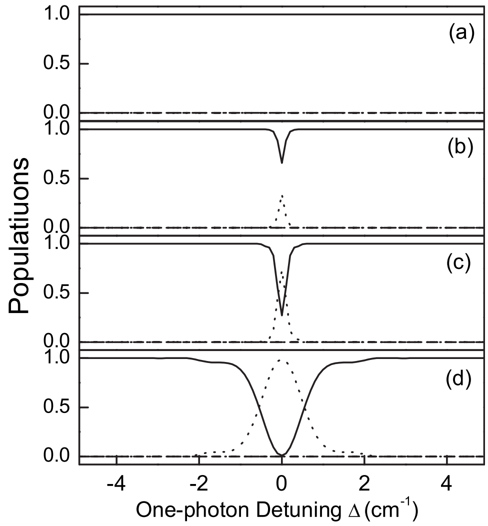

FIG. 2. The final populations in the four states ρ_{11} (dotted line), ρ_{22} (dashed line), ρ_{33} (solid line), and ρ_{44} (dot-dashed line) as a function of the one-photon detunings of the pump and Stokes lasers under different Rabi frequency Ω_c of the control field: $\Omega_p=\Omega_s=2$, $T=20$, $\tau=26$, in corresponding units of cm^{-1}. (a) $\Omega_c=0$, (b) $\Omega c=0.8$, (c) $\Omega_c=1.6$, (d) $\Omega_c=5$.

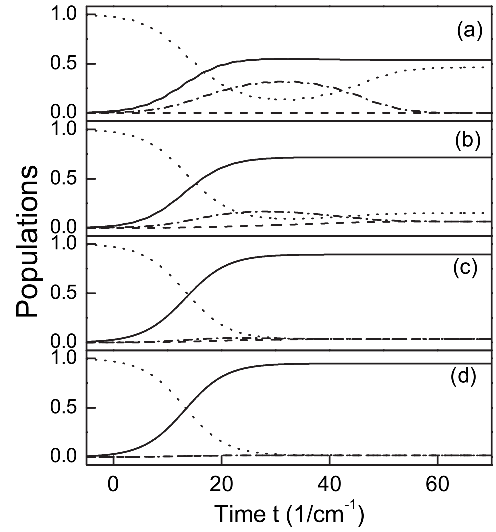

FIG. 3. The time evolution of the populations in the four states ρ_{11} (dotted line), ρ_{22} (dashed line) ρ_{33} (solid line), and ρ_{44} (dot-dashed line) with the three laser fields tuned to the respective resonant transitions under different collision-induced coherence decay rates: $\Omega_c=1$, $\gamma_{13p}=0$, $\gamma_{12p}=\gamma_{23p}=\gamma_{24p}=1p$, and $\gamma_{14p}=\gamma_{34p}=2p$ (p represents the relative buffer gas pressure), and the other parameters are the same as those in Fig. 2. (a) $p=0$, (b) $p=0.03$, (c) $p=0.15$, (d) $p=1$.

level system driven by three laser fields has the similar feature to the driven tripod-type four-level system studied in Refs. [13,14]. However, with the dephasing collisions taken into account, we show in the following that the population transfer can be enhanced dramatically with increasing the collisional decay rates in a moderate range when the three laser fields with nearly equal peak Rabi frequencies are each tuned to resonance with the respective transitions.

III. NUMERICAL RESULTS WITH DENSITY MATRIX EQUATION

When the population relaxation and phase relaxation within the studied system are taken into account, the time evolution of the quantum system could be readily treated with the density matrix equation, which can be written as

$$i\hbar\frac{\partial\rho}{\partial t}=[H,\rho]-i\Gamma\rho, \tag{5}$$

where Γ is the phenomenological decay matrix. We consider the pulse durations are on the picosecond time scale, so the usual population relaxation with decay time on the order of tens of nanoseconds of the atomic or molecular excited states can be neglected during the pulse durations. The collision-induced coherence decay rate between levels i and j is denoted as γ_{ijp} $(i\neq j)$. As studied in Ref. [12], we do not take into account the collisional decay rate between levels 1 and 3, as it is much smaller than the other decay rates (for simplicity, we assume that $\gamma_{12p}=\gamma_{23p}=\gamma_{24p}$, and $\gamma_{14p}=\gamma_{34p}=\gamma_{12p}+\gamma_{24p}$). In what follows, the relative parameters are scaled with cm^{-1}. We numerically integrate the density matrix equation by using the fourth-order Runge-Kutta integrator with the population initially in state 1.

Figure 3 shows the time evolution of the populations in the four states with the three laser fields each tuned to resonance with the respective transitions under different collision-induced coherence decay rates, where the interaction parameters are chosen to ensure adiabatic conditions. In all figures, the time origin is chosen at the peak of the Stokes pulse. As seen from Fig. 3(a), in the absence of the collisions, the population in state 3 increases from zero to a certain value of about 0.54, and the population in state 1 decreases to a lowest value of about 0.13 before reaching a steady value of about 0.46, whereas the population in state 4 reaches a peak value of about 0.32 before relaxing back nearly to zero, and no transient population would reside in state 2. The low efficiency of the population transfer from state 1 to state 3 and a considerable transient population in state 4 during the evolution process are due to the nonadiabatic coupling between the two degenerate adiabatic states φ_0 and φ_1. With the increase of the collision-induced decay rates, the transfer efficiency would increase and the transient populations in state 4 would decrease [see Figs. 3(b) and 3(c)]. Very little populations would reside in state 4 and the transfer efficiency can be improved to about 95% when the collision-induced decay rates are nearly compared to the Rabi frequency of the control field, as shown in Fig. 3(d). Obviously, the transfer efficiency can be enhanced significantly with the increase of the collision-induced decay rates to the value nearly comparable to the Rabi frequency of the control field.

As is well known, the mechanism of the STIRAP [7] is based on CPT [3] (or EIT [4]). In the simplest Λ-type three-level system, the preceding Stokes pulse provides the Autler-Townes splitting of states 2 and 3 and prepares for the lossless transfer process. When the time-separated pump pulse arrives, the interference of the two transition pathways from the initial state 1 to the two Autler-Townes states results in the nonabsorption of the pump laser (i.e., EIT) and the subsequent perfect population transfer. In the present inverse Y-type four-level system, states 1, 2, and 3 form a Λ-type three-level subsystem, and a STIRAP process can occur with the counterintuitive order of the pump and Stokes pulses, which would transfer population from state 1 to state 3. Moreover, states 1, 2, and 4 form a ladder-type three-level subsystem, and a STIRAP process would also take place until the pump pulse nearly reaches its peak Rabi frequency, which would transfer the population from state 1 to state 4 as well; after that time, the control and pump fields form another STIRAP process, which would transfer the population in state 4 back to state 1, as can be seen from Fig. 3(a) that appreciable transient populations in state 4 follow the switching on of the pump pulse. Consequently, only a part of the populations can be transferred from state 1 to state 3. In this case, if we can suppress the transient populations in state 4 during the evolution process, then the transfer efficiency could be enhanced. This can be realized through the collision-controlled EIA in the ladder-type three-level subsystem formed by states 1, 2, and 4.

As discussed by Agarwal [8], whether we have EIT due to destructive interference or EIA due to constructive interference in the driven V-type, Λ-type, and ladder-type three-level systems depends on the structure of the systems and dephasing collisions. According to the analysis in Ref. [8], in the ladder-type (or Λ-type) three-level system formed by states 1, 2, and 4 (or 3), the nature of the interference depends on the sign of the decay term $\gamma_{12p}-\gamma_{14p}$ (or $\gamma_{12p}-\gamma_{13p}$). If $\gamma_{12p}-\gamma_{14p}$ (or γ_{13p})>0, a destructive interference would take place; if $\gamma_{12p}-\gamma_{14p}$ (or γ_{13p})<0, a constructive interference would occur; and if $\gamma_{12p}-\gamma_{14p}$ (or γ_{13p})$=0$, there will be no interference. In the present inverse Y-type four-level system, the collisional decay rate γ_{14p} includes the two decay rates γ_{12p} and γ_{24p}, so $\gamma_{12p}-\gamma_{14p}<0$, and the collision-controlled EIA would take place in the ladder-type three-level subsystem formed by the states 1, 2, and 4, which would suppress the population transfer from state 1 to state 4. On the other hand, we have $\gamma_{12p}-\gamma_{13p}>0$ as we neglect the collisional decay rate between states 1 and 3, so the collision-controlled EIT would occur in the Λ-type three-level subsystem formed by states 1, 2, and 3, which would enhance the population transfer from state 1 to state 3. This can be confirmed from Figs. 3(b)–3(d) that the transient populations in state 4 would decrease and the transfer efficiency would increase with increasing the collision-induced decay rates. Therefore, the population transfer in the four-level system would almost evolve solely along the dark state φ_0, just as that in the Λ-type three-level system, as shown in Fig. 3(d). It should be noted that, in the tripod-type four-level system studied in Refs. [13,14], if we neglect the collision-induced decay rates between state 1 and states 3 and 4, the numerical results show that nearly no enhancement of population transfer from state 1 to state 3 can occur with the increase of the collision-induced decay rates, as shown in Fig. 4. This is due to the fact that in the tripod-type four-level system, the collision-controlled EIT would take place in both of the Λ-type three-level subsystems formed by states 1, 2, and 3 and states 1, 2, and 4; consequently, the collisions nearly have no influence on the population transfer.

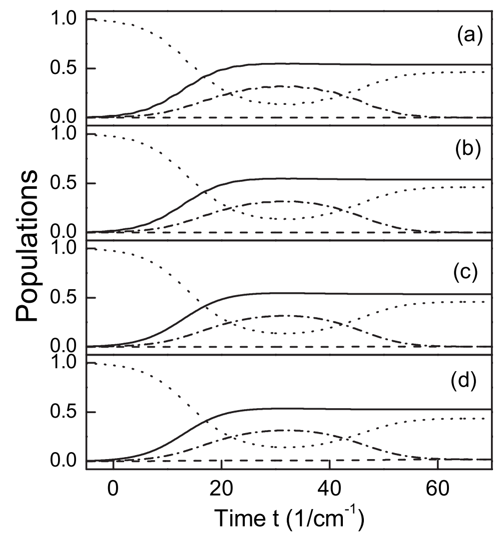

FIG. 4. The time evolution of the populations in the four states ρ_{11} (dotted line), ρ_{22} (dashed line), ρ_{33} (solid line), and ρ_{44} (dot-dashed line) in the tripod-type four-level system with the three laser fields tuned to the respective resonant transitions under different collision-induced decay rates: $\Omega_c=1$, $\gamma_{12p}=\rho_{23p}=\rho_{24p}=1p$ and $\rho_{13p}=\rho_{14p}=\rho_{34p}=0$, and the other parameters are the same as those in Fig. 2. (a) $p=0$, (b) $p=0.03$, (c) $p=0.15$, (d) $p=1$.

The enhanced population transfer via the collision-controlled EIA and EIT can further be seen from the final populations in the four states as a function of the one-photon detunings of the pump and Stokes pulses, as shown in Fig. 5. In the absence of the collisions, nearly complete population transfer to state 3 can be obtained and the transfer efficiency is robust to the one-photon detunings of the two pulse fields due to the adiabaticity except near the one-photon resonances where a narrow dip appears due to the nonadiabatic

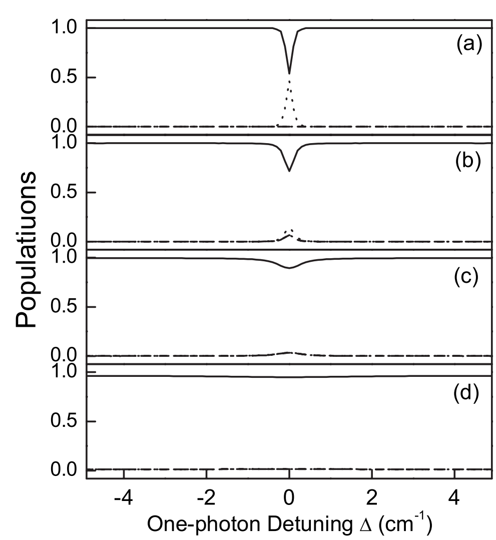

FIG. 5. The final populations in the four states ρ_{11} (dotted line), ρ_{22} (dashed line), ρ_{33} (solid line), and ρ_{44} (dot-dashed line) as a function of the one-photon detunings of the pump and Stokes lasers under different collision-induced decay rates: (a) $p=0$, (b) $p=0.03$, (c) $p=0.15$, (d) $p=1$, and the other parameters are the same as those in Fig. 3.

coupling between φ_0 and φ_1 [see Fig. 5(a)]. Note that, if we reduce the pulse areas of the pump and Stokes fields to such values that the adiabatic limit is not satisfied, then two highest transfer efficiencies appear where the two pulse lasers are tuned to the one-photon resonances with the two dressed states created by the control field. With the increase of the collision-induced decay rates, the depth of the dip becomes smaller, and its width becomes wider. When the decay rates are nearly compared to the Rabi frequency of the control field, the dip almost disappears and the evolution in the four-level system would have a similar feature to that in the Λ-type three-level system, as displayed in Fig. 5(d). It should also be noted that, with increasing the collisional decay rates to the value nearly comparable to the Rabi frequency of the control field, the transfer efficiency would decrease slightly except near the one-photon resonances of the two pulse fields.

It is well known that the STIRAP technique has a distinct feature, i.e., its robustness to small changes in the time delay of the two pulses. Figure 6 shows the transfer efficiency as a function of the time delay between the pump and Stokes pulses with the three laser fields each tuned to resonance with the respective transitions under different collision-induced decay rates. As seen in Fig. 6, the range of the delay time and the magnitude of the transfer efficiency are limited in the absence of the collisions. With the increase of the collision-induced decay rates, both the range of the time delay and the transfer efficiency are increased significantly. It is obvious that both the robustness and efficiency of the population transfer can be improved with the increase of the collision-induced decay rates to the value nearly comparable to the Rabi frequency of the control field despite the dephasing nature of the collisions.

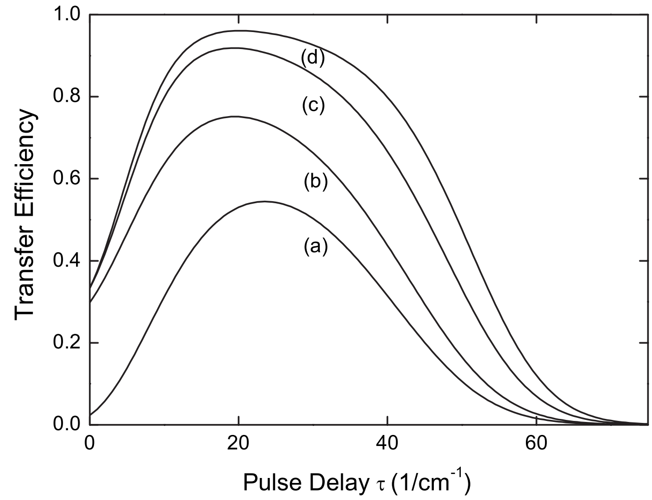

FIG. 6. The transfer efficiency as a function of the time delay between the pump and Stokes pulses with the three laser fields tuned to the respective resonant transitions under different collision-induced decay rates: (a) $p=0$, (b) $p=0.03$, (c) $p=0.15$, (d) $p=1$, and the other parameters are the same as those in Fig. 3.

IV. CONCLUSIONS

We have demonstrated that an arbitrary coherent superposition between an initial state and a target state can be realized either by varying the Rabi frequency of the control laser field or by tuning the one-photon detunings of the pump and Stokes laser fields with a sufficiently strong control field with the stimulated Raman adiabatic passage technique in an inverse Y-type four-level system. Moreover, when the three laser fields with nearly equal peak Rabi frequencies are each tuned to resonance with the respective transitions, the low transfer efficiency due to the nonadiabatic coupling between two degenerate adiabatic states could be enhanced significantly with the increase of the collision-induced coherence decay rates under certain conditions in spite of the dephasing nature of the collisions, which comes from the collision-controlled EIT in the Λ-type three-level subsystem and EIA in the ladder-type three-level subsystem of the four-level system.

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