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Characteristics of ionization probability with adiabatic inversion by stochastic fields

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Adiabatic inversion in two- and three-level systems excited by stochastic fields is investigated. The stochastic electric fields, which are called the chaotic field and the phase-diffusion field, can invert the population of a two-level atom. In a three-level system, we compare the method of sweeping the laser frequency with that of the resonance excitation by lasers that have bandwidths appropriate to the width of Doppler broadening. When the Doppler shift is taken into account, bandwidths of the electric fields are effective to ionize atoms efficiently. When sweeping the first exciting laser frequency, the delay of the second laser pulse increases the ionization probability. If the half width at half maximum of Doppler broadening is narrow and two lasers irradiate atoms simultaneously, the finite bandwidths of the lasers ionize more atoms than sweeping the laser frequency. On the other hand, if the Doppler broadening is large or the second laser irradiates the atoms properly after the first laser, sweeping the first laser frequency is efficient for ionization. Sweeping the laser frequency is not suitable for the system where the intermediate state's spontaneous-decay constant is short. For that system it is efficient to ionize the atoms by lasers that have the finite bandwidth appropriate for the Doppler broadening.

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I. INTRODUCTION

Much attention has been paid recently to the study of multiphoton excitation and/or ionization of atoms. In particular, increasing the ionization probability is of great interest in laser analysis, laser chemistry, and laser isotope separation. Sweeping the laser frequency was proposed for enhancing ionization of atoms [1,2]. On the other hand, it was shown that the bandwidth and the intensity fluctuation of the laser have a large effect on multistep photoionization [3,4]. In this paper, a computational investigation is made to analyze to what extent the ionization probability can be increased by sweeping the laser frequency with the laser bandwidths and the Doppler-broadening effect taken into consideration.

Sweeping the laser frequency to achieve high ionization probability is called adiabatic rapid passage (ARP), which has been intensively studied recently. With this process, the population of two-level atoms is inverted by means of sweeping laser frequency and/or amplitude. The frequency-sweeping excitation is more efficient in some cases than resonant excitation, especially when the levels are split. It was proposed that this could be utilized for isotope separation [5,6]. Meanwhile, the fluctuation of the laser frequency and amplitude has a large effect on the laser-atom interaction. There are two types of laser electric fields. One is the field of the intensity stabilized cw laser, which has only phase fluctuations, and the other is the field of the pulsed multimode laser which has high intensity but large fluctuations of the frequency and amplitude. These fluctuations introduce laser-bandwidth effects on the laser-atom interaction. In order to investigate the difference between the two fields we employ two different models; one is the chaotic-field model, which corresponds to a pulsed multimode laser, and the other is the phase-diffusion model, which is an amplitude stabilized cw laser. The chaotic-field model deals with phase and amplitude fluctuations, while the phase-diffusion model deals only with phase fluctuations.

The method of adiabatic inversion for exciting atoms makes use of coherent effects. The fluctuations of the laser frequency and amplitude, however, destroy the coherent process of multiphoton excitation and ionization. To investigate adiabatic-inversion schemes, therefore, it is very important to take incoherent effects into account.

This paper is intended to give a numerical investigation on the effects of the incoherence on adiabatic excitation and the methods to excite and ionize atoms efficiently in various systems. In Sec. II the atomic system that we consider and the assumed electric fields are summarized and the density-matrix equations are derived for each electric field. We investigate the ionization probability under the various conditions in Sec. III.

II. THEORY

We consider an atom which has a three-level system as indicated in Fig. 1. Each state is denoted the ground state $|1\rangle$, the intermediate state $|2\rangle$, and the autoionization state $|3\rangle$, respectively. Their energy levels are given by $\omega_i = E_i/\hbar \, (i=1,2,3)$.

The first laser whose complex electric field is

$$\mathbf{E}_a(t) = \mathbf{e}_a[\epsilon_a(t)\exp(i\omega_a t) + \text{c.c.}] \quad (1)$$

excites an atom from $|1\rangle$ to $|2\rangle$ and

$$\mathbf{E}_b(t) = \mathbf{e}_b[\epsilon_b(t)\exp(i\omega_b t) + \text{c.c.}] \quad (2)$$

denotes the second laser electric field which excites the atom from $|2\rangle$ to $|3\rangle$. The laser electric fields, therefore, are described as $\mathbf{E}(t) = \mathbf{E}_a(t) + \mathbf{E}_b(t)$. The detunings of

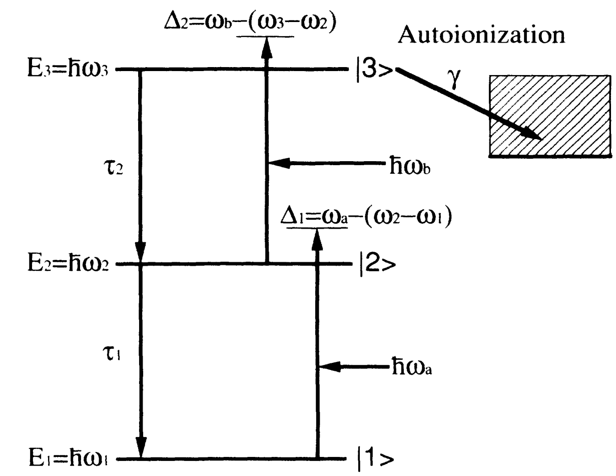

FIG. 1. Schematic energy-level diagram of the three-level system considered in this paper.

the laser frequencies and the transition frequencies are written as $\Delta_1=\omega_a-(\omega_2-\omega_1)$ and $\Delta_2=\omega_b-(\omega_3-\omega_2)$, respectively. The atom is ionized from the autoionization state at a constant rate Γ. The spontaneous decay constant for $|2\rangle\to|1\rangle$ is denoted by τ_1 and that for $|3\rangle\to|2\rangle$ is by τ_2. By the selection rule, the transition from $|3\rangle$ to $|1\rangle$ is forbidden.

The density-matrix equation for Fig. 1 is given by

$$-\frac{\hbar}{i}\frac{\partial\hat{\rho}}{\partial t}=[\hat{H},\hat{\rho}]\ , \tag{3}$$

where $\hat{H}$ is the total Hamiltonian.

A. Chaotic field

In this section we assume that the laser electric fields of Eq. (3) are described as chaotic fields [7]. The chaotic-field description is suitable for thermal light or light from a pulsed multimode laser with a large number of independent modes. The Nth-order correlation function of the electric-field amplitude $\epsilon(t)$ of the chaotic field is given by

$$\langle \epsilon(t_1)^*\cdots\epsilon(t_n)^*\epsilon(t_{n+1})\cdots\epsilon(t_{2n})\rangle =\sum_P\prod_{j=1}^{n}\langle \epsilon^*(t_j)\epsilon(t_{P(j+n)})\rangle\ , \tag{4}$$

where P stands for permutation. Assuming the laser line shape to be Lorentzian, the first-order correlation function can be written

$$\langle \epsilon(t)^*\epsilon(t')\rangle=\langle|\epsilon|^2\rangle e^{-b|t-t'|}\ , \tag{5}$$

with b being the bandwidth of the spectrum. Taking the chaotic field into account,we obtain from Eq. (3) the following density-matrix equations in the rotating-wave approximation [8]:

$$\frac{d}{dt}\sigma_{12}^{nm}=\left[-i\Delta_1-\left[\frac{1}{2\tau_1}+b_a(2n+1)+2mb_b\right]\right]\sigma_{12}^{nm}-i\frac{\Omega_b}{2}(\sqrt{m+1}\sigma_{13}^{nm}-\sqrt{m}\,\sigma_{13}^{nm-1})$$
$$-i\frac{\Omega_a}{2}\sqrt{n+1}(\sigma_{11}^{nm}-\sigma_{11}^{n+1m})+i\frac{\Omega_a}{2}\sqrt{n+1}(\sigma_{22}^{nm}-\sigma_{22}^{n+1m})\ , \tag{6}$$

$$\frac{d}{dt}\sigma_{23}^{nm}=\left\{-i\Delta_2-\left[\frac{1}{2}\left[\frac{1}{\tau_1}+\frac{1}{\tau_2}+\Gamma\right]+2nb_a+(2m+1)b_b\right]\right\}\sigma_{23}^{nm}+i\frac{\Omega_a}{2}(\sqrt{n+1}\sigma_{13}^{nm}-\sqrt{n}\,\sigma_{13}^{n-1m})$$
$$-i\frac{\Omega_b}{2}\sqrt{m+1}(\sigma_{22}^{nm}-\sigma_{22}^{nm+1})+i\frac{\Omega_b}{2}\sqrt{m+1}(\sigma_{33}^{nm}-\sigma_{33}^{nm+1})\ , \tag{7}$$

$$\frac{d}{dt}\sigma_{13}^{nm}=\left\{-i(\Delta_1+\Delta_2)-\left[\frac{1}{2}\left[\frac{1}{\tau_2}+\Gamma\right]+(2n+1)b_a+(2m+1)b_b\right]\right\}\sigma_{13}^{nm}-i\frac{\Omega_b}{2}\sqrt{m+1}(\sigma_{12}^{nm}-\sigma_{12}^{nm+1})$$
$$+i\frac{\Omega_a}{2}\sqrt{n+1}(\sigma_{23}^{nm}-\sigma_{23}^{n+1m})\ , \tag{8}$$

$$\frac{d}{dt}\sigma_{11}^{nm}=-(2nb_a+2mb_b)\sigma_{11}^{nm}+\frac{1}{\tau_1}\sigma_{22}^{nm}+i\frac{\Omega_a}{2}(\sqrt{n+1}\sigma_{21}^{nm}-\sqrt{n}\,\sigma_{21}^{n-1m})-i\frac{\Omega_a}{2}(\sqrt{n+1}\sigma_{12}^{nm}-\sqrt{n}\,\sigma_{12}^{n-1m})\ , \tag{9}$$

$$\frac{d}{dt}\sigma_{22}^{nm}=-\left[\frac{1}{\tau_1}+2nb_a+2mb_b\right]\sigma_{22}^{nm}+\frac{1}{\tau_2}\sigma_{33}^{nm}-i\frac{\Omega_a}{2}(\sqrt{n+1}\sigma_{21}^{nm}-\sqrt{n}\,\sigma_{21}^{n-1m})+i\frac{\Omega_a}{2}(\sqrt{n+1}\sigma_{12}^{nm}-\sqrt{n}\,\sigma_{12}^{n-1m})$$
$$-i\frac{\Omega_b}{2}(\sqrt{m+1}\sigma_{23}^{nm}-\sqrt{m}\,\sigma_{23}^{nm-1})+i\frac{\Omega_b}{2}(\sqrt{m+1}\sigma_{32}^{nm}-\sqrt{m}\,\sigma_{32}^{nm-1})\ , \tag{10}$$

$$\frac{d}{dt}\sigma_{33}^{nm}=-\left[\frac{1}{\tau_2}+\Gamma+2nb_a+2mb_b\right]\sigma_{33}^{nm}+i\frac{\Omega_b}{2}(\sqrt{m+1}\sigma_{23}^{nm}-\sqrt{m}\,\sigma_{23}^{nm-1})-i\frac{\Omega_b}{2}(\sqrt{m+1}\sigma_{32}^{nm}-\sqrt{m}\,\sigma_{32}^{nm-1})\ , \tag{11}$$

with $n,m=0,1,2,\ldots$ denoting the correlation order of each laser, and where

$$\Omega_a=2\hbar^{-1}\mu_{12}\langle|\epsilon_a|\rangle^{1/2}\ , \tag{12}$$

$$\Omega_b=2\hbar^{-1}\mu_{23}\langle|\epsilon_b|\rangle^{1/2}\ , \tag{13}$$

are the Rabi frequencies of the first and second lasers with μ_{12},μ_{23} being the dipole matrix elements of $|1\rangle\leftrightarrow|2\rangle$ and $|2\rangle\leftrightarrow|3\rangle$.

The population of each level is given by

$$\langle\sigma_{ii}\rangle=\sigma_{ii}^{00}\ . \tag{14}$$

The ionization probability, therefore, is denoted by

$$\langle P(t)\rangle=1-\sigma_{11}^{00}-\sigma_{22}^{00}-\sigma_{33}^{00}\ . \tag{15}$$

The above (n,m) density-matrix equations must be solved numerically to obtain the ionization probability.

B. Phase-diffusion model

The phase-diffusion model corresponds to an intensity-stabilized single-mode laser and has only the phase fluctuations. The Nth-order correlation function of the phase-diffusion model satisfies

$$\langle\epsilon(t_1)^*\cdots\epsilon(t_n)^*\epsilon(t_{n+1})\cdots\epsilon(t_{2n})\rangle=\prod_{j\,odd}^{2n-1}\langle\epsilon^*(t_j)\epsilon(t_{P(j+1)})\rangle\ . \tag{16}$$

For the phase-diffusion model the density-matrix equations of Eq. (3) can be derived in the following way [9]:

$$\frac{d}{dt}\sigma_{12}=\left[-i\Delta_1-\left[\frac{1}{2\tau_1}+2b_a\frac{\beta_a^2}{\Delta_1^2+\beta_a^2}\right]\right]\sigma_{12}-i\frac{\Omega_b}{2}\sigma_{13}+i\frac{\Omega_a}{2}(\sigma_{22}-\sigma_{11})\ , \tag{17}$$

$$\frac{d}{dt}\sigma_{23}=\left[-i\Delta_2-\frac{1}{2}\left[\frac{1}{\tau_1}+\frac{1}{\tau_2}+\Gamma\right]+2b_b\frac{\beta_b^2}{\Delta_2^2+\beta_b^2}\right]\sigma_{23}+i\frac{\Omega_a}{2}\sigma_{13}+i\frac{\Omega_b}{2}(\sigma_{33}-\sigma_{22})\ , \tag{18}$$

$$\frac{d}{dt}\sigma_{13}=\left[-i(\Delta_1+\Delta_2)-\frac{1}{2}\left[\frac{1}{\tau_2}+\Gamma\right]+2b_a\frac{\beta_a^2}{\Delta_1^2+\beta_a^2}+2b_b\frac{\beta_b^2}{\Delta_2^2+\beta_b^2}\right]\sigma_{13}-i\frac{\Omega_b}{2}\sigma_{12}+i\frac{\Omega_a}{2}\sigma_{23}\ , \tag{19}$$

$$\frac{d}{dt}\sigma_{11}=\frac{1}{\tau_1}\sigma_{22}+\mathrm{Im}\Omega_a\sigma_{12}\ , \tag{20}$$

$$\frac{d}{dt}\sigma_{22}=-\frac{1}{\tau_1}\sigma_{22}+\frac{1}{\tau_2}\sigma_{33}-\mathrm{Im}\Omega_a\sigma_{12}+\mathrm{Im}\Omega_b\sigma_{23}\ , \tag{21}$$

$$\frac{d}{dt}\sigma_{33}=-\left[\frac{1}{\tau_2}+\Gamma\right]\sigma_{33}-\mathrm{Im}\Omega_b\sigma_{23}\ . \tag{22}$$

Ω_a and Ω_b are the first and second Rabi frequencies and the ionization probability for the phase-diffusion model is

$$\langle P_{\mathrm{ion}}(t)\rangle=1-\sigma_{11}-\sigma_{22}-\sigma_{33}\ . \tag{23}$$

The cutoff parameter β makes the laser line shape Lorentzian near the center but cuts off the wings of the laser spectrum. In other words, for $\Delta\ll\beta$ the effective laser linewidth can be written approximately as

$$2b\frac{\beta^2}{\Delta^2+\beta^2}\approx 2b\ , \tag{24}$$

which corresponds to being Lorentzian, while for $\Delta\gg\beta$ the laser linewidth

$$2b\frac{\beta^2}{\Delta^2+\beta^2}\approx 0 \tag{25}$$

can be ignored.

C. Adiabatic inversion sweeping

The following condition is adopted to occur the adiabatic inversion:

$$\Delta(0)=-\Delta_{\mathrm{sweep}}\ , \tag{26}$$

$$\Delta(T_L)=\Delta_{\mathrm{sweep}}\ , \tag{27}$$

where T_L is the interaction time, and Δ_{sweep} the sweeping range [10]. We choose the linear sweep for the detuning Δ_{12}

$$\Delta_{12}=\lambda t-\Delta_{\mathrm{sweep}}\ , \tag{28}$$

where

$$\lambda=\frac{2\Delta_{\mathrm{sweep}}}{T_L}\ . \tag{29}$$

To simplify and to analyze only the effect of the change of the laser frequency, only the first frequency is swept while the second laser frequency is kept constant and the Rabi frequencies are not changed for the interaction time.

We analyze in the following section under the condition that the Rabi frequencies Ω_a and Ω_b are set to be 1 GHz. We also assume that $\tau_1=100$ nsec, $\tau_2=500$ nsec, $\Gamma=0.5$ nsec^{-1}, and that the first and second lasers pulse duration are 20 nsec.

III. RESULTS AND DISCUSSION

A. Two-level system

At first, in order to confirm the effect of the laser bandwidth and compare two assumed electric fields for sweeping, we investigate a two-level system.

1. Chaotic field

Figure 2 shows time evolution of the $|2\rangle$ population for the chaotic field with the laser bandwidth being 0 GHz. The population of $|2\rangle$ does not show Rabi oscillation even in the case of resonance. The maximum value of $|2\rangle$ is approximately 90% at about 12 nsec. When the

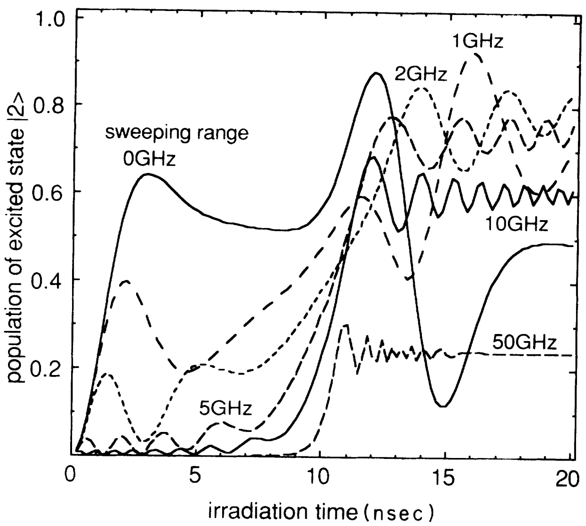

FIG. 2. Time evolution of the |2⟩ population. The chaotic field (CF) is used for the laser electric field. The laser bandwidth b_a is 0 GHz.

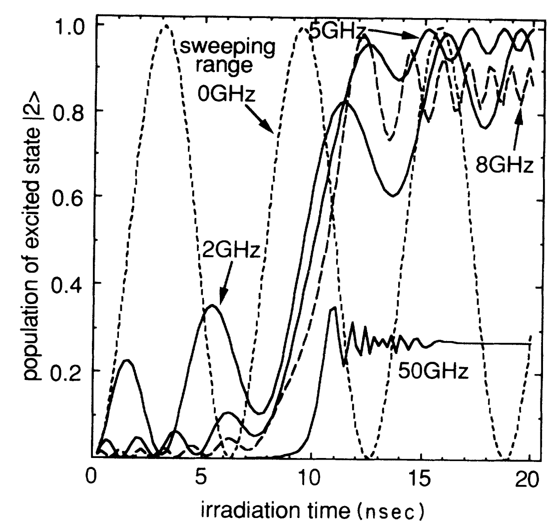

FIG. 4. Time evolution of the |2⟩ population. The phase-diffusion model (PDM) is used for the laser electric field. The laser bandwidth b_a is 0 GHz.

laser frequency is swept from 1.0 to 10.0 GHz, we can observe that population inversion occurs. The sweeping range of 1.0 GHz achieves the highest population inversion with laser bandwidth 0 GHz. For the sweeping range of 50.0 GHz, population inversion is negligible.

For the laser bandwidth 0.1 GHz, we see in Fig. 3 that the population inversion takes place, but the sweeping range of 5.0 GHz inverts the population at only 10%. This figure shows that on this condition the clear adiabatic inversion does not occur. From Figs. 2 and 3 for the chaotic field the population inversion decreases as the laser bandwidth increases.

2. *Phase-diffusion model*

Figure 4 displays time evolution of |2⟩ population in the case that the laser electric field is assumed to be the phase-diffusion model with the laser bandwidth being 0.0 GHz. This corresponds to the classical electric field. It means both the laser electric amplitude and frequency are stabilized. The Rabi oscillation occurs without the frequency being swept. The population inversion is fulfilled with sweeping ranges from 2.0 to 8.0 GHz. The population inversion does not take place with the sweeping range of 50 GHz.

Figure 5 shows the time evolution of the |2⟩ population on the condition that it is assumed that the laser electric field is the phase-diffusion field and the laser bandwidth is 0.1 GHz. The population |2⟩ does not depend on the sweeping ranges expanding from 0.0 to 2.0 GHz. But the sweepings of 5.0 and 10.0 GHz make the population inverted. For the phase-diffusion model when there exists a laser bandwidth, the population inversion is

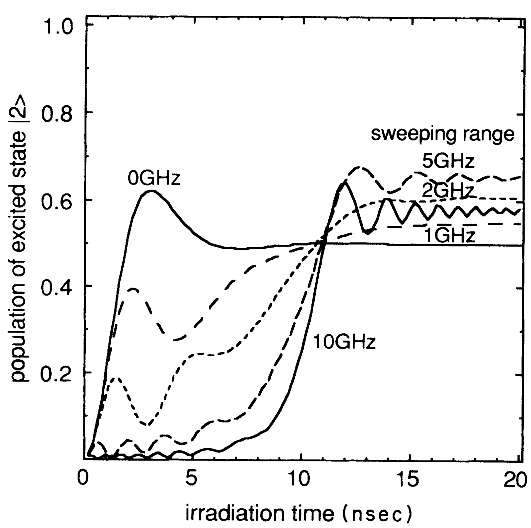

FIG. 3. Time evolution of the |2⟩ population. The CF is used for the laser electric field. The laser bandwidth b_a is 0.1 GHz.

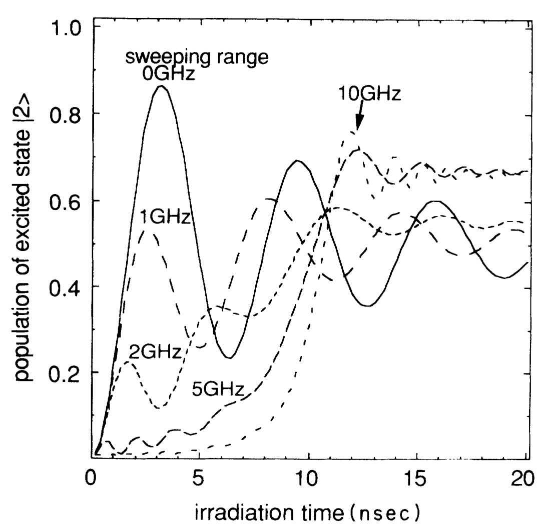

FIG. 5. Time evolution of the |2⟩ population. The PDM is used for the laser electric field. The laser bandwidth b_a is 0.1 GHz.

smaller and the sweeping range required for population inversion is larger in the two-level system.

B. Three-level system

From Figs. 1–5 the population inversion occurs at the midpoint of the interaction time. Therefore it can be considered that the second laser pulse is delayed in order to ionize atoms efficiently. We analyze the three-level system on the condition that the laser electric field is assumed to be the phase-diffusion model and the laser bandwidth is 0 GHz (i.e., the laser electric field is the classical electric field).

Figure 6 shows the ionization probability as a function of the delay of the second laser pulse on the various sweeping ranges. In the case that the first and second lasers irradiate the atoms simultaneously, the highest ionization probability is acquired without the frequency being swept. But the delay of the second laser pulse for sweeping makes the ionization probability higher. For the sweeping range 2.0 GHz the ionization probability is about 97.5% at the delay time 8 nsec. The highest ionization probability of the sweeping range 1.0 and 5.0 GHz is about the same value as that without the frequency swept. The sweeping range of 8.0 GHz is too large to sweep. It is expected that there is the optimal delay time and the sweeping range for the system. It is about 2.0 GHz at 8 nsec for this three-level system.

C. Effect of Doppler broadening

Doppler shift is important because an atom is moving against the laser light when the atom interacts with the laser light. We investigate the effect of Doppler broadening on the ionization probability in the three-level system. For the numerical calculation Doppler broadening can be taken into account in the following way [11].

On the two-level system of which the Bohr frequency is

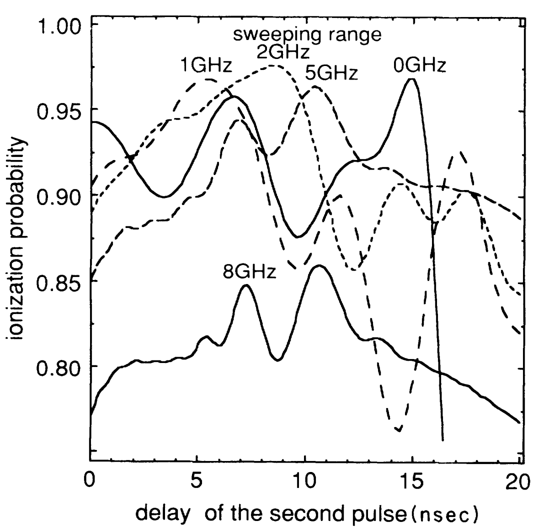

FIG. 6. Ionization probability as a function of the delay of the second laser pulse. The PDM is used for the laser electric field. The first laser bandwidth b_a is 0 GHz.

ω, the atom has a velocity v against the laser light. According to the Doppler effect, the laser frequency ω' absorbed by the atom is

$$\omega' = \frac{\omega}{1-(v/c)} \simeq \omega \left[1+\frac{v}{c} \right] , \tag{30}$$

where c is the speed of light. Therefore, this Doppler shift introduces the detuning Δ_{Dopp},

$$\Delta_{\text{Dopp}} = \omega' - \omega \simeq \omega \frac{v}{c} . \tag{31}$$

It is assumed that the atoms are irradiated by the two collinear laser lights. Therefore Doppler shifts of the first and the second ladders Δ^1_{Dopp}, Δ^2_{Dopp} can be written as

$$\Delta^1_{\text{Dopp}} \simeq \omega_1 v/c \equiv \Delta_{\text{Dopp}} , \tag{32}$$

$$\Delta^2_{\text{Dopp}} \cong \omega_2 v/c \simeq \Delta_{\text{Dopp}} . \tag{33}$$

It follows that the detuning of the three-level system is

$$\Delta^1_{\text{Dopp}} + \Delta^2_{\text{Dopp}} \cong 2\Delta_{\text{Dopp}} . \tag{34}$$

The distribution function of the velocity $f(v)$ at temperature T obeys the Maxwell-Boltzmann distribution,

$$f(v) \propto \exp(-mv^2/2k_B T) , \tag{35}$$

where m is an atomic mass and k_B is the Boltzmann constant. It follows that the distribution function of Doppler shift is

$$g(\Delta_{\text{Dopp}}) = \frac{T^*}{\pi} \exp \left[-\frac{(T^* \Delta_{\text{Dopp}})^2}{\pi} \right] , \tag{36}$$

where T^* satisfies

$$(ku)^2 = \frac{\pi}{(T^*)^2} \tag{37}$$

with k being the number vector of the laser light and u is the average velocity of the atom. The half width at half maximum (HWHM) of Doppler broadening b_{Dopp} is described with T^* as follows:

$$b_{\text{Dopp}} = \sqrt{\pi \ln 2}/T^* \cong \frac{1.5}{T^*} . \tag{38}$$

In the case that Doppler broadening of an absorption spectrum is taken into account, the ionization probability is described by

$$P_{\text{Dopp}}(t) = \int_{-\infty}^{\infty} P(t;\Delta_{\text{Dopp}}) g(\Delta_{\text{Dopp}}) d\Delta_{\text{Dopp}} , \tag{39}$$

where $P(t;\Delta_{\text{Dopp}})$ is the ionization probability for the detuning by Doppler shift Δ_{Dopp} and $g(\Delta_{\text{Dopp}})$ is the distribution function of the detuning by Doppler shift [Eq. (36)].

In the following we will investigate the effect of Doppler broadening on the ionization probability.

1. Effect of laser bandwidth on the atom with Doppler broadening

Figures 7 and 8 show the ionization probability as a function of the HWHM of Doppler broadening on the

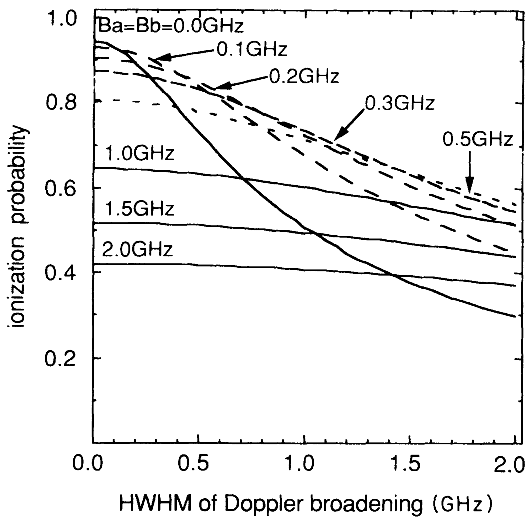

FIG. 7. Ionization probability as a function of the HWHM of Doppler broadening for the various laser bandwidths. The laser field is assumed to be that of the PDM.

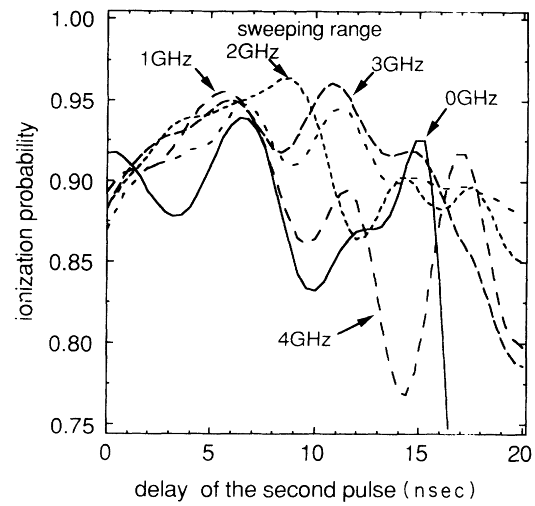

FIG. 9. Ionization probability as a function of the delay of the second laser pulse. The HWHM of Doppler broadening is 0.1 GHz.

conditions that the laser electric field is the phase-diffusion model (Fig. 7) or the chaotic field (Fig. 8). They indicate that the ionization probability of the phase-diffusion model is more dependent on the laser bandwidth than that of the chaotic field. The laser bandwidth of the maximum ionization probability increases as the HWHM of Doppler broadening increases. Either field has the optimal laser bandwidth for the ionization probability on the HWHM of Doppler broadening. Without Doppler broadening (i.e., the HWHM of Doppler broadening is 0 GHz), the laser bandwidth of the maximum ionization probability is 0 GHz in the phase-diffusion model, but it is 0.1 or 0.2 GHz in the chaotic field. The maximum ionization probability in the phase-diffusion model is higher than that in the chaotic field.

2. *Effect of Doppler broadening on the ionization probability for sweeping*

It was proved in Sec. III A that the laser light of the phase-diffusion model was suitable for the adiabatic inversion. Therefore, for the phase-diffusion model we investigate the effect of Doppler broadening on the ionization probability for sweeping the laser frequency.

Figures 9 and 10 show the ionization probability as a function of the second laser pulse delay on the various sweeping ranges on the condition that the HWHM of Doppler broadening is 0.1 GHz (Fig. 9) and 1.0 GHz (Fig. 10). In Fig. 9 the maximum ionization probability

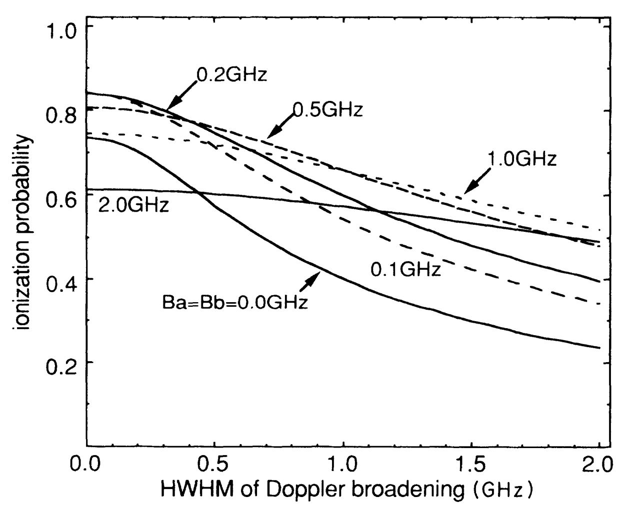

FIG. 8. Ionization probability as a function of HWHM of Doppler broadening for the various laser bandwidths. The laser field is assumed to be CF.

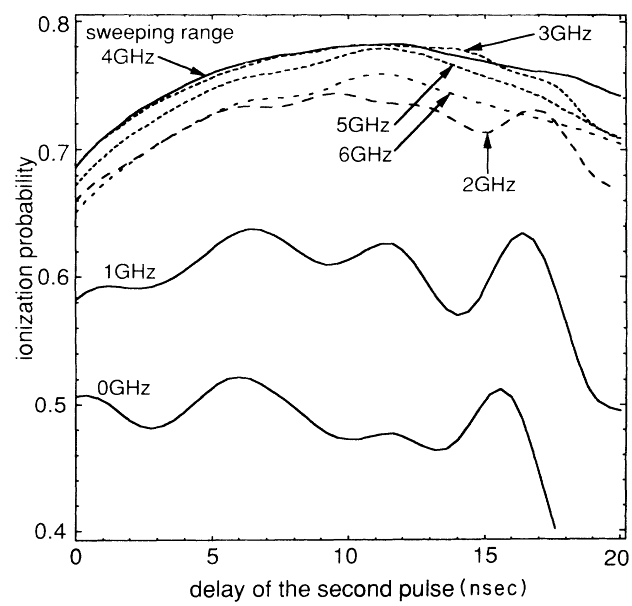

FIG. 10. Ionization probability as a function of the delay of the second laser pulse. The HWHM of Doppler broadening is 1.0 GHz.

with the delay being 0 nsec is acquired at the sweeping range 0 GHz. On the other hand, if the delay of the second laser pulse is introduced, the maximum ionization probability increases. In Fig. 9 the ionization probability is approximately 96% at 9-nsec delay with the sweeping range being 2.0 GHz. The delay of the second laser pulse is very effective for the ionization probability to be higher.

In Fig. 10 the dependence of the ionization probability on the delay of the second laser is smaller than that in Fig. 9. Without delay, the ionization probability with the sweeping range of 3.0 GHz is the highest. The change of the sweeping range between 2.0 and 6.0 GHz does not have much effect on the ionization probability.

The ionization probability in Fig. 9 is higher than that in Fig. 10 because the Doppler broadening of Fig. 10 is larger than that of Fig. 9. The ionization probability of Fig. 9 is also sensitive to the delay of the second laser pulse. On the condition that Doppler broadening is large, the sweeping range is needed to be larger corresponding to Doppler broadening in order to ionize atoms efficiently.

D. Sweeping for a short-lifetime atom

For multistep photoionization the characteristics of intermediate states are very important. If the spontaneous-decay constant of the intermediate state which belongs to the three-level system is much shorter than the atom-laser interaction time, the population of $|3\rangle$ decays before the laser irradiation time is finished. So the achievement of the adiabatic inversion is difficult. The atom is not excited again since the laser frequency is detuned to the resonance frequency at that time.

It is considered to be effective that the atom is excited by the laser which has the bandwidth appropriate to the linewidth of the absorption spectrum when the spontaneous decay time of the intermediate state is short. We investigate a three-level system that has 10 nsec as the decay time of level $|2\rangle$.

Figure 11 shows the dependence of the ionization probability on the HWHM of Doppler broadening. This shows a similar result to Fig. 7. The ionization probability of Fig. 11 is a little lower than that of Fig. 7 because the decay time of the intermediate state is short.

Figure 12 shows the ionization probability with the laser frequency swept as a function of the delay time of the second pulse. The ionization probability is maximum when the sweeping range is 0 GHz (i.e., always resonant) and the delay time is 0 nsec (i.e., simultaneous irradiation). It decreases as the delay time increases while the delay makes it increase in the system that has 100 nsec for the $|2\rangle$ decay time. In other words, sweeping the laser frequency in this scheme is not effective in order to ionize atoms efficiently.

According to Figs. 11 and 12, when the spontaneous-decay time of the intermediate state is short and there is Doppler broadening, the higher ionization probability is given by the laser that has the appropriate bandwidth rather than by sweeping the laser frequency.

IV. CONCLUSION

We have investigated the effect of phase and amplitude fluctuations on the three-level ionization system with the adiabatic excitation. On the condition that the absorption spectrum has Doppler broadening, more atoms are ionized by an amplitude-stabilized cw laser than by a pulsed multimode laser, and some bandwidths of the laser are needed to ionize the atoms efficiently.

The adiabatic inversion occurs in either the chaotic-field or the phase-diffusion model when sweeping the fre-

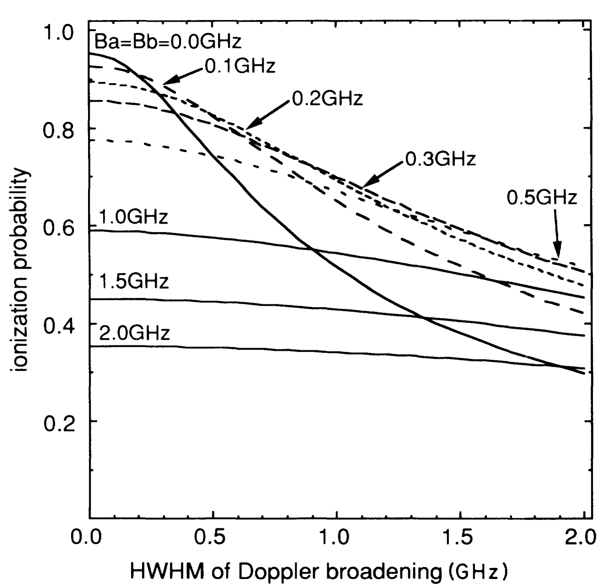

FIG. 11. Ionization probability as a function of the HWHM of Doppler broadening for the various laser bandwidths. The laser field is assumed to be that of the PDM. The spontaneous-decay time of the intermediate state is 10 nsec.

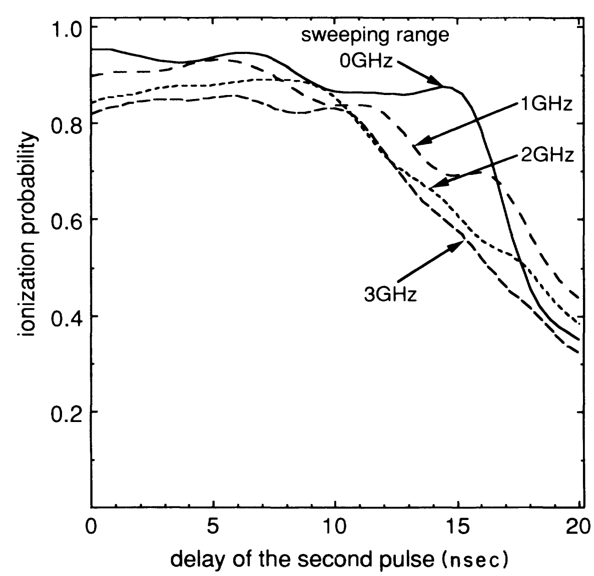

FIG. 12. Ionization probability as a function of the delay of the second laser pulse for the various sweeping range.

quency. The inversion can take place more easily when the laser bandwidth, which is due to incoherence, is narrower.

In the three-level system, which is irradiated simultaneously with the first and second lasers, sweeping the first laser frequency is very helpful to ionize the atoms, especially when Doppler broadening is broad. And the increases of the ionization probability owing to the frequency sweeping become more remarkable by the delay of the second laser pulse than by the simultaneous irradiation. There is an optimal frequency range of sweeping depending on Doppler broadening. In the system where the intermediate state has the short spontaneous-decay constant, the frequency sweeping is not effective, and therefore the atom is excited efficiently by a laser that has a bandwidth appropriate for Doppler broadening.

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