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Time-dependent spectrum of resonance fluorescence for atoms prepared in pure dressed states

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We study the transient fluorescence spectra of two-level atoms driven by a strong optical field when the atoms are initially prepared in pure dressed states of the atom-field Hamiltonian. Spectra obtained here differ qualitatively from those observed in the steady state. In the case of steady-state resonant excitation, a three-peaked spectrum symmetric about the laser frequency is obtained; with pure-dressed-state preparation, the symmetry of the spectrum about the driving field is broken—one side peak is initially enhanced and the other is initially suppressed. Furthermore, the temporal oscillations of fluorescence intensity observed in previous calculations of transient fluorescence spectra appropriate to atoms prepared in a superposition of dressed states [J. H. Eberly *et al.*, J. Phys. B 13, 217 (1980)] are suppressed when pure-dressed-state preparation is considered.

I. INTRODUCTION

It is well known that the steady-state fluorescence spectrum of an ensemble of two-level atoms irradiated by a strong, nearly resonant cw laser field consists of three spectral components (peaks) and is a symmetric spectrum about the laser frequency.[1-3] A physical understanding of this phenomenon can be achieved by using a dressed-atom description of the atom-field interaction.[3,4] In the dressed-atom approach, eigenstates of the atom plus laser field serve as the basis states for the system. The three spectral components of the steady-state fluorescence spectra, whose features are independent of initial atomic conditions, are viewed as arising from transitions among the "dressed" states.

Fluorescence spectra obtained under transient conditions may be qualitatively different from the spectra observed in the steady state. Recently, Eberly, Kunasz, and Wódkiewicz analyzed the time-dependent spectrum of resonance fluorescence[5] by using the quantum regression theorem[6] and the Eberly-Wódkiewicz counting-rate definition of the spectrum (physical spectrum).[7] They studied the dynamic evolution of the emission spectrum following the sudden excitation of a "two-level" atom by a nearly resonant laser field. Formal analytic expressions for transient spectra as a function of laser field strength, atomic lifetime, laser-atom detuning, and the bandwidth of the spectrometer (for example, a Febry-Perot interferometer) used to analyze the spectrum were obtained. They specifically calculated the time-dependent spectra for atoms prepared in four different initial states. The calculated transient spectrum retains its symmetric, three-peaked structure for a strong resonant driving field. For a strong, nonresonant driving field the transient spectrum is asymmetric at any finite time t; as $t \rightarrow \infty$, however, the spectrum becomes symmetric about the laser frequency in this steady-state limit.[2,3] In both the resonant and nonresonant cases, the spectral peaks displayed an initial damped oscillation in amplitude as a function of time. Time-dependent resonance fluorescence has also been studied by others.[8,9] In particular, the spectrum of resonance fluorescence following the removal of a strong cw field was calculated by Huang *et al.*[10] In the course of previous work on transient fluorescence spectra, however, only a limited set of initial conditions have been studied.

Recently, we developed a theory of transient spectra for the somewhat related problem of probe spectra in strongly driven three-level systems.[11] We assumed that an ensemble of three-level atoms was prepared with arbitrary initial conditions and then exposed at $t=0$ to a strong driving field and a weak probe field each tuned close to resonance with one of two coupled transitions. As expected, we found that all transient probe spectra ultimately evolved to the well-known steady-state Autler-Townes doublet structure. However, we found that two distinctly different types of transient spectra could be observed depending on whether the atoms were initially prepared in a pure dressed state or not. For atoms initially in a pure *atomic* (i.e., bare) state, the transient probe spectrum obtained with a resonant driving field retains the symmetric double-peaked structure found in the steady state, but the spectral peaks display damped amplitude oscillations as they approach their steady-state heights. On the other hand, for atoms initially prepared in a pure dressed state, again working with a resonant driving field, one of the probe peaks is initially suppressed and the spectral peaks approach their steady-state magnitudes in an essentially nonoscillatory manner. It should be noted that the preparation of pure dressed states using amplitude and phase-controlled resonant excitation fields has recently been demonstrated experimentally.[12]

It is the purpose of this paper to study the transient resonance fluorescence spectra arising from atoms initially prepared in a pure dressed state. Comparison is made with transient fluorescence spectra like those calculated by Eberly *et al.*[5] that arise from atoms initially in a nonpure dressed state. The probe spectra described above lead one to suspect that transient fluorescence spectra arising from atoms prepared in a pure dressed state or in a superposition of dressed states will display interesting differences. Indeed, we find that our spectra differ qualitatively from those given by Eberly *et al.* In particular, for resonant excitation of atoms prepared in a pure dressed state, one of the fluorescence peaks is suppressed at early times (i.e., the spectrum is no longer symmetric). In addition, the approach to equilibrium of the resonance peaks is essentially nonoscillatory, in contrast with the results obtained when the atoms are not prepared in pure dressed states. A simple physical interpretation of these results is given below, based on a dressed-atom picture (DAP) of resonance fluorescence.

II. DRESSED ATOM PICTURE OF RESONANCE FLUORESCENCE

It is well known[3,4] that for a strong, nearly resonant monochromatic laser field, the energy-level structure in the conventional DAP appears as an infinite set of equally spaced doublets. The states $|\alpha_n\rangle$ and $|\beta_n\rangle$ in a given doublet are linear combinations of the states $|1,n\rangle$ and $|2,n-1\rangle$, where n is the photon number for the field and "1" and "2" refer to atomic states. The centers of adjacent dressed-state doublets are split by $\hbar\omega_l$, where ω_l is the laser frequency, and the splitting between the two states $|\alpha_n\rangle$ and $|\beta_n\rangle$ within each doublet is $(\Delta^2+\chi^2)^{1/2}$, where $\Delta=\omega_{21}-\omega_l$ is the atom-field detuning (ω_{21} is the atomic transition frequency), $\chi=\mathbf{p}_{21}\cdot\mathbf{E}_0/\hbar$ is the Rabi frequency associated with the laser field, $\mathbf{E}_0$ is the field amplitude, and $\mathbf{p}_{21}$ is an atomic dipole matrix element. The Rabi frequency χ is chosen to be real and positive and it is assumed that $\chi \gg \gamma$, the decay rate from level 2 to 1. One need only consider the transition between two neighboring doublets to deduce the fluorescence spectrum.

Fluorescence is represented in the DAP as transitions from one doublet to the doublet below, the intensity of each fluorescence component is proportional to the population of the dressed state from which the transition originates.[13] Under typical initial conditions, both the lower dressed state $|\alpha_n\rangle$ and the upper one $|\beta_n\rangle$ have some initial populations [see Fig. 1(a)]. At early times, spontaneous transitions occur on four different transitions with three different transition frequencies [ω_l and $\omega_l \pm(\Delta^2+\chi^2)^{1/2}$]. The initial state of the system can be specified by the bare (i.e., atomic) state density matrix elements $\tilde\rho_{11}$, $\tilde\rho_{22}$, $\tilde\rho_{12}$, and $\tilde\rho_{21}$ at $t=0$ before application of the step-function pulse. Since the dressed-state definitions depend on the field present for $t>0$, one cannot specify the initial dressed-state density matrix elements without specifying the field. If the applied field for $t>0$ is a resonant one ($\Delta=\omega_{21}-\omega_l=0$), then the dressed-state density matrix elements are related to the bare state ones by[14]

$$\tilde\rho_{\alpha_n\alpha_n}=(1+\tilde\rho_{12}+\tilde\rho_{21})/2\ ,$$

$$\tilde\rho_{\beta_n\beta_n}=(1-\tilde\rho_{12}-\tilde\rho_{21})/2\ ,$$

$$\tilde\rho_{\alpha_n\beta_n}=(\tilde\rho_{\beta_n\alpha_n})^*=(\tilde\rho_{22}-\tilde\rho_{11}+\tilde\rho_{12}-\tilde\rho_{21})/2\ .$$

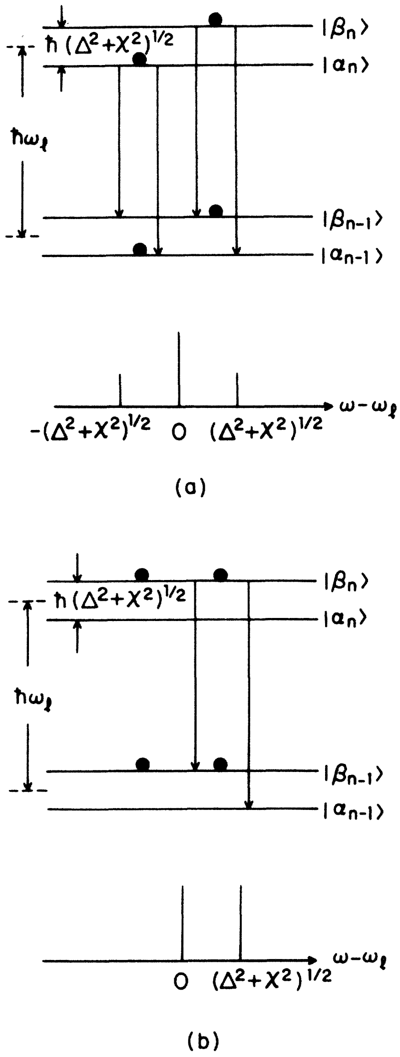

FIG. 1. Fluorescence transitions and the corresponding fluorescence spectrum of a two-level atom at early times following a sudden excitation by a strong, nearly resonant laser field for different initial atomic conditions: atoms are initially prepared (a) in a superposition of dressed states and (b) in a pure dressed state, $|\beta_n\rangle$.

For atoms initially in their ground state at $t=0$, $\tilde\rho_{\alpha\alpha}=\tilde\rho_{\beta\beta}=-\tilde\rho_{\alpha\beta}=-\tilde\rho_{\beta\alpha}=\frac{1}{2}$ (equal population of dressed states plus coherence between dressed states). Moreover, for any initial conditions in which $\tilde\rho_{12}=-\tilde\rho_{21}$, one finds equal population of the dressed states. All of the initial conditions discussed by Eberly *et al.*[5] for the resonant field fall into this category. The spectrum observed with the resonant field is symmetric about the laser frequency ω_l and the three spectral peaks build up simultaneously.

On the other hand, when atoms are initially prepared in a pure dressed state, e.g., the upper dressed state $|\beta_n\rangle$ [see Fig. 1(b)], the situation changes dramatically. Since, at $t=0$, only state $|\beta_n\rangle$ is occupied, one finds spontaneous transitions originating from this state only at $t=0$. These transitions correspond to spectral peaks having frequencies ω_l and $\omega_l+(\Delta^2+\chi^2)^{1/2}$. Thus, at early times, the lower-frequency-side peak is suppressed. Moreover, the amplitude of the higher-frequency-side peak relative to the central peak is larger than for the case of atoms initially in their ground state since, for pure-dressed-state preparation, the initial dressed-state population leading to this side peak is enhanced relative to the initial dressed-state populations leading to the central peak. These considerations imply that the fluorescence spectrum displays only two peaks with separation $(\Delta^2+\chi^2)^{1/2}$ at early times. At later times, after some population accumulates in the lower dressed state $|\alpha_n\rangle$ as a result of fluorescence, the lower-frequency-side peak starts to build up and the intensity difference between the central peak and the upper-frequency-side peak increases. As a result, the transient fluorescence spectrum is not symmetric about the laser frequency ω_l even for a resonant laser field ($\Delta=0$). As time progresses, however, fluorescence cascades equilibrate the relative dressed-state populations and the spectrum assumes its symmetric steady-state form.

III. CALCULATION OF THE SPECTRUM

The influence of the pure-dressed-state initial condition on the transient fluorescence spectrum is illustrated most clearly if one assumes a resonant laser field. Consequently, we limit our calculation to a detuning $\Delta=0$. Also, since the suppression and enhancement of the two side peaks are most obvious when the three spectral peaks are well separated, we restrict the discussion to situations in which the Rabi frequently χ is much larger than the decay rate γ from excited state 2 back to the ground state 1.

The time-dependent fluorescence spectrum is calculated for an initial condition in which atoms are prepared in a pure dressed state and, for comparison, for an initial condition in which the atoms are initially in their ground state (equal populations for the dressed states).

We use the method initiated by Eberly, Kunasz, and Wódkiewicz,[5] i.e., the quantum regression theorem[6] and the Eberly-Wódkiewicz (normalized) counting-rate definition of the spectrum (physical spectrum),[7] and follow the notation in their paper[5] (except for Rabi frequency and decay rate).

For a detuning $\Delta=0$, the three sets of initial conditions in which atoms are prepared into the lower dressed state $|\alpha_n\rangle$, the upper one $|\beta_n\rangle$, and the ground state 1 correspond to

$$\psi_\alpha(0)=\begin{bmatrix}\frac{1}{2}\\0\\\frac{1}{2}\end{bmatrix},\quad \psi_\beta(0)=\begin{bmatrix}-\frac{1}{2}\\0\\-\frac{1}{2}\end{bmatrix},\quad \psi_0(0)=\begin{bmatrix}0\\-1\\0\end{bmatrix}, \tag{1}$$

respectively.[11,14] [The vector $\psi(0)$ has components $\tilde{\rho}_{12}(0)$, $\tilde{\rho}_{22}(0)-\tilde{\rho}_{11}(0)$, $\tilde{\rho}_{21}(0)$, respectively.] Proceeding in a manner identical to Eberly *et al.*,[5] we obtain the time-dependent resonance fluorescence spectrum in the limit $\Delta=\omega_{21}-\omega_l=0$, $\chi\gg\gamma$ as

$$I_{\alpha,\beta}(t,\omega,\Gamma)=\tfrac{1}{2}\Gamma\,\mathrm{Re}[G(t,D,\Gamma)\pm H(t,D,\Gamma)]\,, \tag{2a}$$

$$I_0(t,\omega,\Gamma)=\tfrac{1}{2}\Gamma\,\mathrm{Re}[G(t,D,\Gamma)+F(t,D,\Gamma)]\,, \tag{2b}$$

where

$$\begin{aligned}G(t,D,\Gamma)={}&p_1^{-1}[(1-e^{-\Gamma t})/\Gamma-(1-e^{-p_2t})/p_2]+c_3p_3(1-e^{-\Gamma t})/\Gamma\\&+c_3c_4[(\chi^2-p_3p_4)(1-e^{-p_4t}\cos\chi t)-\chi(p_3+p_4)e^{-p_4t}\sin\chi t]\,,\end{aligned} \tag{3a}$$

$$H(t,D,\Gamma)=-ic_3\{\chi(e^{-\Gamma t}-e^{-\gamma t/2})/(\tfrac{1}{2}\gamma-\Gamma)+c_6[\chi(p_3+p_6)(e^{-p_4t}\cos\chi t-e^{-\gamma t/2})+(p_3p_6-\chi^2)e^{-p_4t}\sin\chi t]\}\,, \tag{3b}$$

$$\begin{aligned}F(t,D,\Gamma)={}&p_1^{-1}c_5[e^{-3\gamma t/4}(p_5\cos\chi t+\chi\sin\chi t)-p_5e^{-p_2t}]+p_8^{-1}c_3(p_3\cos\chi t-\chi\sin\chi t)(e^{-3\gamma t/4}-e^{-p_4t})\\&+c_7(p_1^{-1}+c_3p_3)[e^{-3\gamma t/4}(p_7\cos\chi t-\chi\sin\chi t)-p_7e^{-\Gamma t}]+c_7c_3\chi[\chi e^{-\Gamma t}-e^{-3\gamma t/4}(\chi\cos\chi t+p_7\sin\chi t)]\,,\end{aligned} \tag{3c}$$

$$p_{1,2}=\tfrac{1}{2}\gamma\mp\tfrac{1}{2}\Gamma+iD\,, \tag{4a}$$

$$p_{3,4}=\tfrac{3}{4}\gamma\mp\tfrac{1}{2}\Gamma+iD\,, \tag{4b}$$

$$p_{5,6}=\mp\tfrac{1}{4}\gamma+\tfrac{1}{2}\Gamma+iD\,, \tag{4c}$$

$$p_7=\tfrac{3}{4}\gamma-\Gamma\,, \tag{4d}$$

$$p_8=\tfrac{1}{2}\Gamma+iD\,, \tag{4e}$$

$$c_i=(\chi^2+p_i^2)^{-1},\quad i=3,4,5,6,7, \tag{5}$$

and Γ is the full width at half maximum of the (effectively Lorentzian) transmission peak of the Fabry-Perot interferometer used to measure the frequency spectrum of the fluorescence, D is the detuning of the Fabry-Perot line center above the laser frequency ω_l, i.e., $D=\omega-\omega_l$, and subscripts α,β, and 0 represent the three initial conditions listed in Eq. (1) with the corresponding subscripts.

The functions G, H, and F have property

$$G^*(t,D,\Gamma)=G(t,-D,\Gamma)\,, \tag{6a}$$

$$H^*(t,D,\Gamma)=-H(t,-D,\Gamma)\,, \tag{6b}$$

$$F^*(t,D,\Gamma)=F(t,-D,\Gamma)\,, \tag{6c}$$

respectively. Consequently, the functions $I(t,\omega,\Gamma)$ have the properties that

$$I_0(t,\omega_l+D,\Gamma)=I_0(t,\omega_l-D,\Gamma)\ , \tag{7a}$$

$$I_\alpha(t,\omega_l+D,\Gamma)=I_\beta(t,\omega_l-D,\Gamma)\ , \tag{7b}$$

$$I_\beta(t,\omega_l\pm D,\Gamma)=\tfrac{1}{2}\Gamma\ \mathrm{Re}[G(t,D,\Gamma)\mp H(t,D,\Gamma)]\ , \tag{7c}$$

namely, that the physical spectrum arising from atoms initially in their ground state is symmetric about the laser frequency ω_l, while the spectrum arising from atoms prepared in a pure dressed state $|\alpha_n\rangle$ or $|\beta_n\rangle$ are related by Eq. (7b), neither spectrum being symmetric about ω_l for finite time t. The difference between the two side peaks for atoms prepared in pure dressed states is obtained from Eq. (7c) as $\Gamma\,|\,\mathrm{Re}H(t,\chi,\Gamma)\,|$.

As $t\rightarrow\infty$, both H and F vanish, while G has the limiting value

$$G(\infty,D,\Gamma)\sim p_1^{-1}[(1/\Gamma)-(1/p_2)]+c_3p_3/\Gamma$$
$$+c_3c_4(\chi^2-p_3p_4)\ . \tag{8}$$

It follows from Eq. (2) that I_α, I_β, and I_0 corresponding to atoms prepared in the lower dressed state $|\alpha_n\rangle$, the upper dressed state $|\beta_n\rangle$, or the atomic ground state have the same steady-state symmetric physical spectrum as they must. Equation (8), together with Eqs. (4) and (5), allows one to conclude that the physical spectrum of resonance fluorescence in the steady-state limit displays three peaks, at $\omega=\omega_l$ (central peak $D=0$) and at $\omega=\omega_l\pm\chi$ (two side peaks $D=\pm\chi$). The ratio of the amplitude of the central to side peaks in the steady-state limit depends on the ratio Γ/γ. For $\chi\gg\gamma\gg\Gamma$ the ratio is 3:1; for $\chi\gg\Gamma\gg\gamma$ it is 2:1.

IV. ILLUSTRATIVE SPECTRUM

Equations (2) for the physical spectrum of resonance fluorescence are functions of the full width of the transmission peak of the Fabry-Perot interferometer Γ, the detuning D of the Fabry-Perot line center above the laser frequency, the field strength χ, and the time t. For fixed Γ and χ, one can obtain time-dependent physical spectra by monitoring the fluorescence as a function of D for fixed t. Alternatively, for fixed Γ and χ, one can observe transient buildup of the fluorescence as a function of t for fixed D. In the following part, we give illustrative figures of both the transient buildup at the three fluorescence peaks and the full time-dependent physical spectrum of resonance fluorescence.

A. Transient buildup of fluorescence peaks

The fluorescence spectrum displays three peaks, at $D=\omega-\omega_l=0$ (central peak) and $D=\pm\chi$ (two side peaks). We graph the transient buildup of I_β and I_0 at the three fluorescence peaks for $\chi=20\gamma$ and $\Gamma=10\gamma$, 5γ, 2γ, 0.6γ, and 0.2γ, respectively in Fig. 2, in which nonoscillatory lines are for I_β and oscillatory lines are for I_0. These figures illustrate several features.

(1) For atoms initially prepared in the upper dressed state (corresponding to curves I_β) the higher-frequency-side peak is enhanced, and the lower one is suppressed compared with the case in which atoms are initially in the ground state (corresponding to curves I_0), which agree with our previous qualitative discussion.

(2) The I_0 peaks build up with small oscillation of frequency χ, while the I_β peaks build up without oscillation except for some slight oscillation of the suppressed peaks at early times ($\gamma t\lesssim 1$). The oscillation in the I_0 case comes from the precession of the Bloch vector about the driving field vector with frequency χ (since $\Delta=0$).[15] The oscillations of the three I_0 peaks are in phase since they are all related to the upper *atomic* state population, which oscillates with frequency χ. The amplitude of the fluorescence oscillation is intrinsically damped because it is averaged over the time scale of the atomic lifetime $1/\gamma$. Moreover, it is further smoothed by the temporal response time $1/\Gamma$ of the interferometer. Thus, the oscillation amplitudes of the I_0 peaks decrease with decreasing Γ. The absence of oscillation versus time in the case of I_β is linked to the fact that, with pure-dressed-state preparation, the Bloch vector and the driving field vector are initially parallel;[9,11,12] for $t>0$ the Bloch vector $\mathbf{B}$ is effectively "locked" to the field vector $\mathbf{\Omega}_B$ (i.e., the Bloch equation is $d\mathbf{B}/dt\approx\mathbf{\Omega}_B\times\mathbf{B}\approx 0$) and does not precess as it approaches its steady-state value on a time scale given by the spontaneous decay rate. If the dressing field is off resonance, the absence of oscillation in the fluorescence intensity with corresponding dressed-state preparation should also occur.

(3) The suppression and enhancement of the two side peaks are more dramatic for larger ratios of Γ/γ. This can be understood by noting that the interferometer rise time is of order $1/\Gamma$, while the dressed-state populations are equilibrated by radiative cascade on a time scale $1/\gamma$. Thus for $\Gamma/\gamma\ll 1$, the dressed-state populations are equal for most of the recording time of the interferometer; consequently, the suppression and enhancement of the two side peaks is not so dramatic.

(4) The manner in which fluorescence peaks reach their steady-state value is different for I_β and I_0. For I_0, the side peaks approach their equilibrium values from below; while for I_β, one side peak approaches its equilibrium value from above and the other from below.

(5) The intensities of the three peaks increase with decreasing Γ/γ ratio, since the so-called physical spectrum is a normalized counting rate spectrum[7] and the use of a narrow bandwidth interferometer gives a narrow peaked spectrum. The relative size of the physical spectrum intensities from plot to plot does not correspond to the relative size of the observed intensities. The observed intensity should correspond to the unnormalized counting rate spectrum, which is just $\Gamma/4$ times the physical spectrum. When the physical spectra shown in Fig. 2 are converted to the unnormalized counting rate spectra, they decrease with decreasing Γ/γ as might be expected.

B. Time-dependent physical spectrum of resonance fluorescence

The full time-dependent physical spectrum of resonance fluorescence arising from atoms initially in the upper indressed state $|\beta_n\rangle$, I_β, and in the ground state 1, I_0, are generated in Figs. 3 and 4, respectively, for $\mathcal{X}=20\gamma$ and $\Gamma=5\gamma$ (Fig. 3) and 2γ (Fig. 4). The intensities of the spectra in Figs. 3 and 4 are normalized so that their central peaks have the same steady-state height. In addition to the several features mentioned above, one may note the following.

(1) At very early times ($\mathcal{X}t \ll 1$), the spectra are independent of interferometer detuning $D=\omega-\omega_l$ for $|D| \lesssim 2\mathcal{X}$; this result is consistent with energy-time uncertainty arguments.

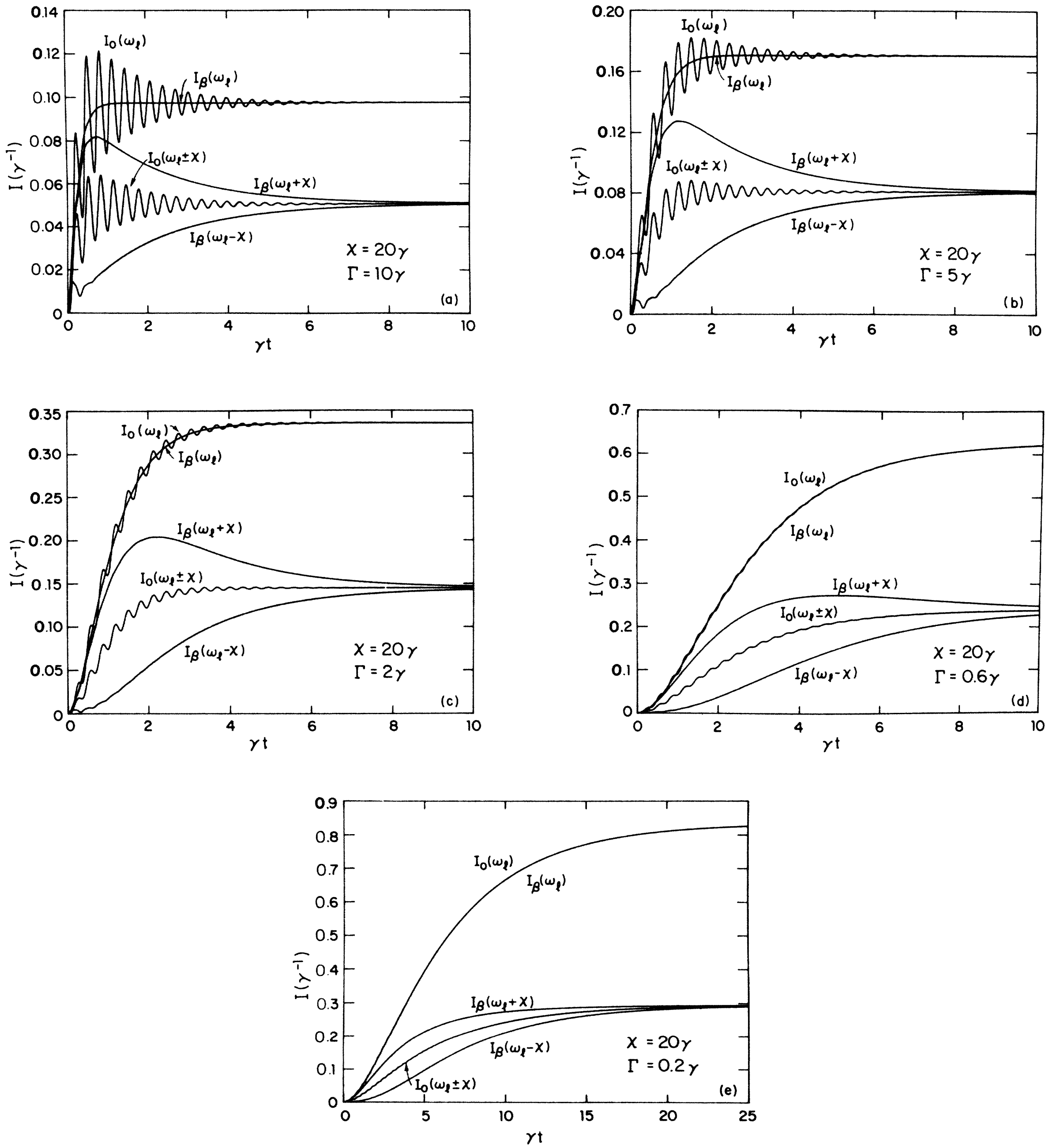

FIG. 2. Transient buildup of fluorescence peaks for $\mathcal{X}=20\gamma$ and different values of Γ/γ: (a) $\Gamma=10\gamma$, (b) $\Gamma=5\gamma$, (c) $\Gamma=2\gamma$, (d) $\Gamma=0.6\gamma$, (e) $\Gamma=0.2\gamma$. Oscillatory curves I_0 are for atoms initially in their ground state and nonoscillatory curves I_β are for atoms initially prepared in the pure dressed state $|\beta_n\rangle$. The units of intensity are in units of γ^{-1} consistent with the definition of the physical spectrum given by Eberly *et al.* (Refs. 5 and 7). The applied field is resonant, $\Delta=\omega_{21}-\omega_l=0$.

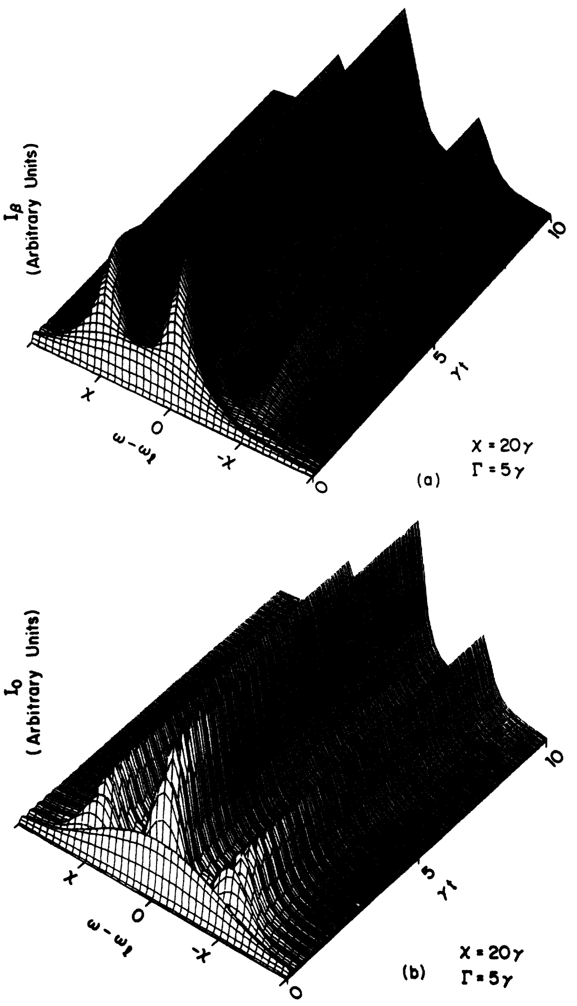

FIG. 3. Time-dependent physical spectrum of resonance fluorescence arising from atoms initially (a) prepared in the pure dressed state $|\beta_n\rangle$, I_β, and (b) in their ground state 1, I_0, for $X=20\gamma$ and $\Gamma=5\gamma$. The applied field is resonant, $\Delta=0$.

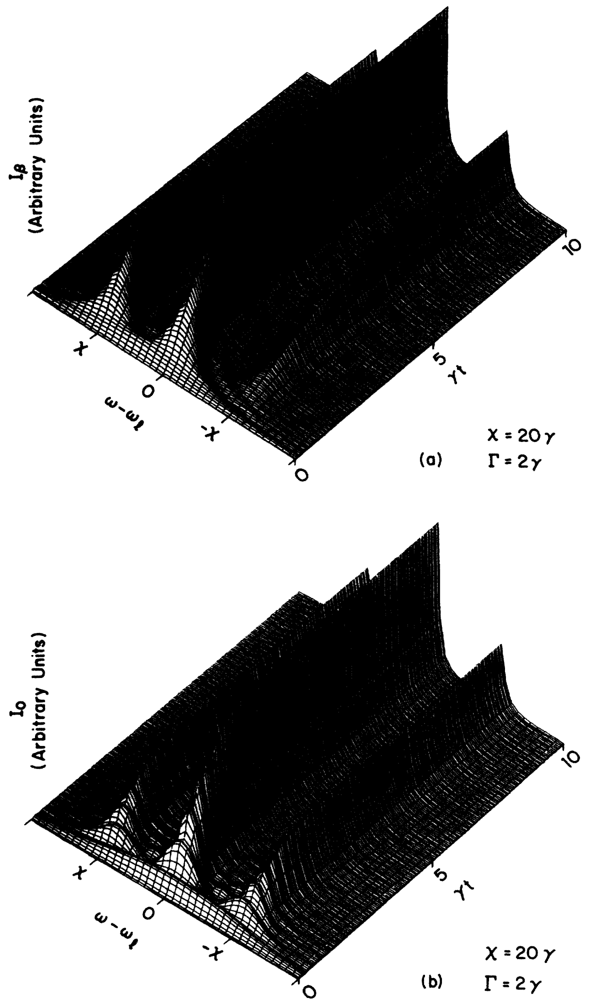

FIG. 4. Same as in Fig. 3 except that $X=20\gamma$ and $\Gamma=2\gamma$. The spectra are normalized so that their central peak's steady-state height is the same as that in Fig. 3.

(2) Spectra from atoms initially in the ground state are symmetric about laser frequency ω_l for the assumed detuning $\Delta=\omega_{21}-\omega_l=0$.

(3) However, the spectrum from atoms initially prepared in the upper dressed state $|\beta_n\rangle$ is *not* symmetric about laser frequency ω_l for $\Delta=0$ and displays, at early times, only two peaks (central peak and the higher-frequency-side peak).

V. CONCLUSION

In conclusion, we have shown that, for an ensemble of two-level atoms irradiated by a strong, nearly resonant laser field, the time-dependent physical spectrum of resonance fluorescence arising from atoms initially prepared in a pure dressed states is quite different from that arising from atoms initially in a superposition of dressed state as discussed by Eberly *et al.*[5] The effect of selectively preparing atoms in a pure dressed state is to suppress one of the two side peaks normally expected in transient resonance fluorescence spectra when both dressed states are populated and to enhance the other. With a resonant driving field, the transient symmetric triplet spectrum displayed when the atoms are prepared in an equal admixture of dressed states becomes asymmetric with pure-dressed-state preparation, and in fact, at early times, the spectrum consists of only the central peak and one side peak. In addition, with pure-dressed-state preparation, the resonance peaks approach their steady-state values in an essentially nonoscillatory manner.

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[13] The fluorescence intensity also depends on the dipole matrix elements between the doublets. For resonant excitation, all such matrix elements are equal, but for nonresonant excitation they can differ significantly (see Ref. 3).

[14] Note that $\chi = \mathbf{p}_{21} \cdot \mathbf{E}_0 / \hbar > 0$ now, while in Ref. 11, $\chi < 0$. Consequently, $-\pi/2 \leq \theta \leq 0$ now.

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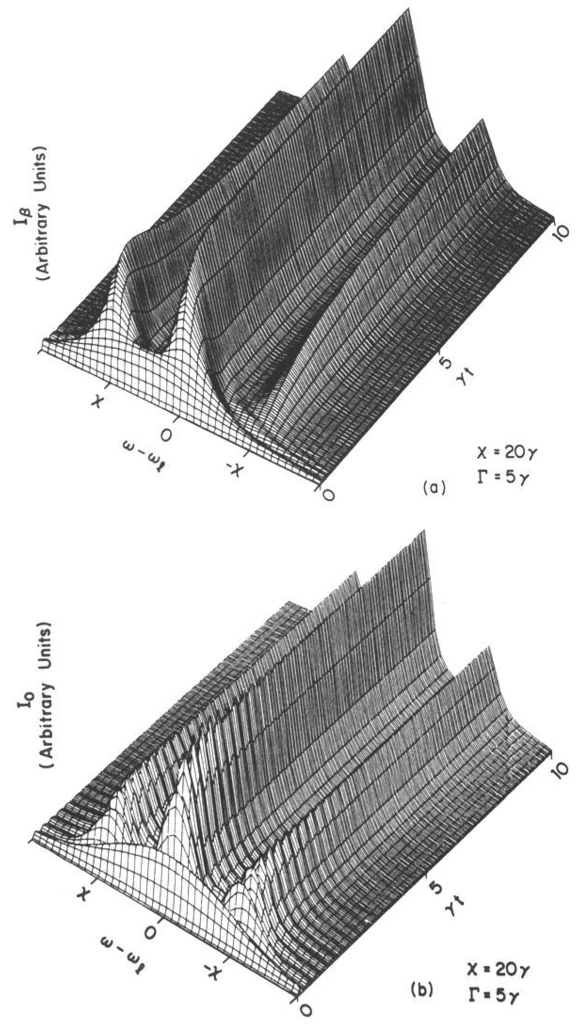

FIG. 3. Time-dependent physical spectrum of resonance fluorescence arising from atoms initially (a) prepared in the pure dressed state $|\beta_n\rangle$, I_β, and (b) in their ground state 1, I_0, for $\chi = 20\gamma$ and $\Gamma = 5\gamma$. The applied field is resonant, $\Delta = 0$.

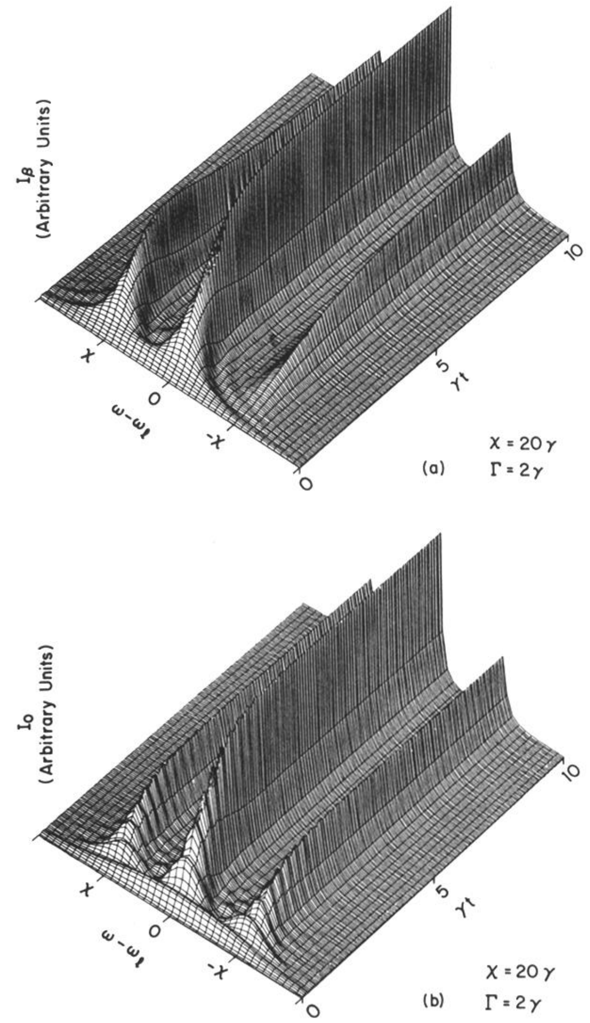

FIG. 4. Same as in Fig. 3 except that $\chi = 20\gamma$ and $\Gamma = 2\gamma$. The spectra are normalized so that their central peak's steady-state height is the same as that in Fig. 3.