Laser-induced "two-atom" coherence

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Our analysis shows that if an electromagnetic field excites a coherent superposition of states of two different types of atoms, then the results of a collision of those two atoms can be quite different from the usual dephasing that a coherently excited atom suffers upon collision with another atom. We present the concept of "two-atom" coherence as one feature of this interaction where the field of a given wavelength may interact with the system coherently over a wide range of internuclear distances.

It is known that the coherence in single or multiphoton interactions of coherent radiation with isolated atoms is destroyed by collisions with other atoms (one-atom system). This study shows the existence of a new coherent effect in the two-photon interaction of coherent radiation with atoms undergoing binary collisions: laser-induced "two-atom" coherence. In this effect, the dephasing effects in the two-atom system caused by their collisional interaction are eliminated, thus allowing the electromagnetic field to interact coherently with the system over a wide range of interatomic distances.

The basic idea here is as follows.[1-3] We have found, theoretically, that if a single electromagnetic field excites coherent superpositions of states of two different types of atoms, then the results of a collision of those two atoms is something quite different from the usual dephasing that a coherently excited atom suffers upon collision with an unexcited partner or one excited but from a different source of excitation. The results of such a collision are expected to show many distinctive and interesting features resulting from interferences that are possible because the relative phases of the excitation of the two individual atoms are traceable to a single common reference, the field at $t=0$.

One feature of this effect, which we present in this paper, arises in a process where both atoms initially in their ground states end up excited as a result of the collision-radiative interactions (two-photon radiative collision).[4,5,1] In the process, the well-known dephasing due to the collision becomes intensity and detuning modulated. This allows for the control of the phase of the final product state relative to that of the initial product state. In fact, by appropriate choice of parameters this phase difference can be eliminated completely for a wide range of internuclear separations (phase resonance), and the process behaves as a two-atom coherent interaction. Our results show, as expected, that when these conditions are achieved, the absorption cross section of the colliding system enjoys an enhancement.

Although the possibility of multiphoton radiative collisions has been previously suggested,[4] it is only recently that experimental and theoretical efforts have dealt with it.[5] During the collision of Ba and Tl ground-state atoms, two photons were absorbed from a single electromagnetic field which resulted in the simultaneous excitation of both atoms. The results of this experiment were analyzable in terms of a one-atom system where only one of the atoms is coherently driven by the electromagnetic field as shown in Fig. 1(a). In our previous work[1-3] we showed that the two-photon radiative collision is much richer than this simple picture since the two atoms can be simultaneously driven by the electromagnetic field as shown in Fig. 1(b).

In this paper we present detailed numerical studies of the absolute line shape and cross section, their dependence on the intensity of the radiation, and give an explanation of the effect in terms of two-atom coherence. We find

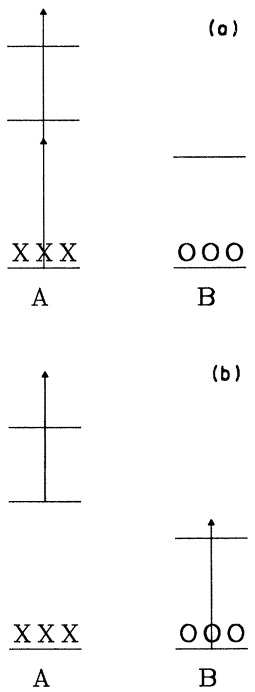

FIG. 1. (a) Simplified schematic showing the field-atom interaction in the case of one-atom system. The field produces a coherent superposition of states of atom A only. (b) Simplified schematic showing the field-atom interaction in the case of two-atom system. The field produces a coherent superposition of states of atoms A and B.

that the absorption line shape of the two-atom system exhibits intensity-induced shifts in contrast to that of the one-atom case. The line shape of the former exhibits symmetry accompanied by an enhancement of the peak of the cross section at intensities where the phase difference between the initial and final scattering states goes through zero (phase resonance).

We consider the collision of atoms A and B in their ground states $|0a\rangle$ and $|0b\rangle$ in the presence of the radiation field $\vec{\epsilon}=\vec{E}_0\cos(\omega t)$ which does not resonate with any of the transitions in either atom. We are interested in the process where both atoms emerge from the interaction excited to $|1a\rangle$ and $|1b\rangle$, respectively. Consider first the case where the field coherently interacts only with atom A as shown in Fig. 2(a) (one-atom system). The state vector of the system is taken to be of the form

$$|\psi(t)\rangle=a_0(t)|0a\rangle|0b\rangle+a_1(t)|1a\rangle|0b\rangle\exp(i\omega_1 t)$$
$$+a_2(t)|2a\rangle|0b\rangle\exp[i(\omega_1+\omega_2)t]$$
$$+a_3(t)|1a\rangle|1b\rangle\exp[i(\omega_1+\omega_3)t]\ ,$$

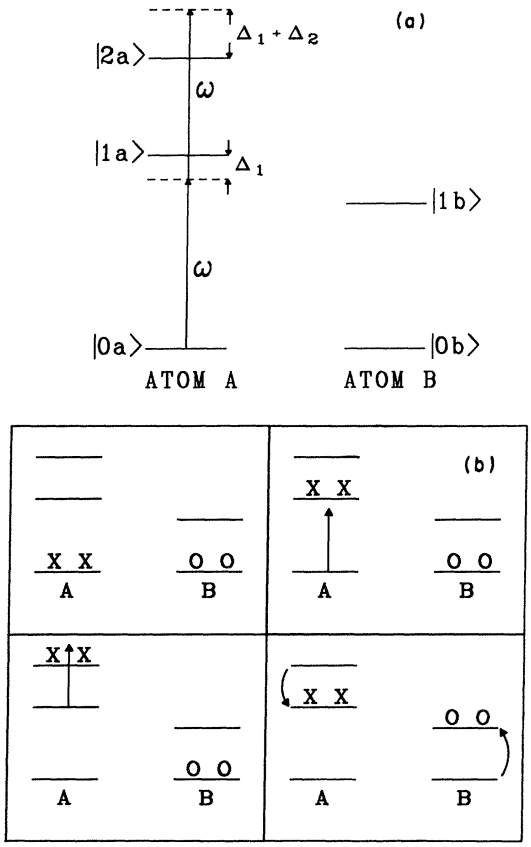

FIG. 2. (a) Partial energy-level diagram showing the relevant levels, transitions, and detunings for the case of one-atom system. In this case the field excites only atom A directly. (b) Set of simplified energy levels showing the sequence of interactions for the case of one atom interacting with the field. The straight arrows represent photon absorption while the curved arrows represent state changes due to collisions.

where $\omega_1=E_{1a}$, $\omega_2=E_{2a}-E_{1a}$, and $\omega_3=E_{1b}$. In the process the initial state $|0a\rangle|0b\rangle$ is virtually excited by the electromagnetic field to the state $|1a\rangle|0b\rangle$, which in turn is virtually excited by the electromagnetic field to the state $|2a\rangle|0b\rangle$. Finally, a collisional transfer from $|2a\rangle|0b\rangle$ to $|1a\rangle|1b\rangle$ nearly conserves the overall energy for the transition [Fig. 2(b)]. The time-dependent Schrödinger equation of this system gives the following coupled equations for the time-dependent coefficients:

$$\frac{da_0}{dt}=i\mu_{1A}E_0\exp(i\Delta_1 t)a_1\ ,$$
$$\frac{da_1}{dt}=i\mu_{1A}^*E_0\exp(-i\Delta_1 t)a_0+i\mu_{2A}E_0\exp(i\Delta_2 t)a_2\ ,$$
$$\frac{da_2}{dt}=i\mu_{2A}^*E_0\exp(-i\Delta_2 t)a_1+iV_2\exp(i\Delta_0 t)a_3\ ,$$
$$\frac{da_3}{dt}=iV_2^*\exp(-i\Delta_0 t)a_2\ ,$$

where $\Delta_1=\omega_1-\omega$, $\Delta_2=\omega_2-\omega$, $\Delta_0=\omega_3-\omega_2$, μ_{iA} is the matrix element of the dipole moment μ_{iz} of atom A in units of $\hbar$, and V_2 is the matrix element $\langle 1a|\langle 1b|V_{ABz}|2a\rangle|0b\rangle/\hbar$.

It is to be noted that in this interaction the electromagnetic field excites a coherent superposition of states of atom A, while the collision results in the excitation of states of atom B. This system of four coupled levels can be reduced, using the adiabatic approximation,[1] to an effective two-level system comprised of the initial and final states of amplitudes a_0 and a_3, respectively:

$$\frac{da_0}{dt}+i(b_i'E_0^2+b_2'E_0^4)a_0=ic_0'E_0^2V_2\exp(i\delta t) \qquad (1)$$

and

$$\frac{da_3}{dt}+ib_3V_2^2a_3=ic_3'E_0^2V_2\exp(i\delta t)\ , \qquad (2)$$

where b_i' and c_i' are functions of the various detunings and $\delta=\Delta_1+\Delta_2+\Delta_0$ is the detuning from exact resonance.

It is also to be noted that the ground state is Stark shifted by the amount $b_1'E_0^2+b_2'E_0^4$ which over the time of collision for long pulses can be taken to be flat. On the other hand, the final state is collisionally shifted by an amount $b_3V_2^2$ which depends on the internuclear separation R and, hence, on time since V_2 is a function of R. It is often helpful in discussing such collisions to view the overall interaction in terms of transitions between the levels of a quasimolecule formed during the time of collisions. Figure 3 shows a schematic of the interatomic potential in this model. The lower level corresponds to the state $|0a\rangle|0b\rangle$ and is constant for all R. The upper level corresponds to the state $|1a\rangle|1b\rangle$ and is strongly curved at small R. The two levels are seen to be two-photon resonant until R becomes small enough that the upper level begins to curve. This is the usual "dephasing" associated with collisional interactions. The transition probability of the process in the weak-field limit is given by[1]

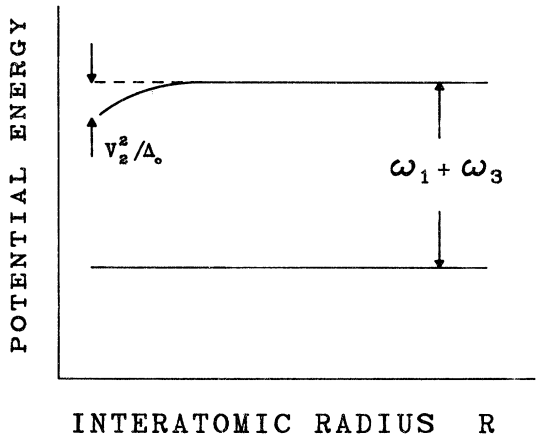

FIG. 3. Schematic of the interatomic potential as a function of R, the internuclear distance, for the one-atom system.

$$|a_3|^2=4\alpha^2E_0^4\left|\int_0^\infty R^{-3}(t)\cos\left[\int_0^t(CR^{-6}+\delta)dt\right]dt\right|^2, \tag{3}$$

with

$$\alpha^2=\frac{\hbar^2\mu_{1A}^2\mu_{2A}^2\mu_{1B}^2}{[\Delta_1(\Delta_1+\Delta_2)]^2} \tag{4}$$

and

$$C=\frac{\hbar^2\mu_{2A}^2\mu_{1B}^2}{\Delta_0}, \tag{5}$$

where $R^2=b^2+v^2t^2$ is the square of the internuclear distance, v is the relative velocity, and b is the impact parameter. Note that $\Delta_1+\Delta_2$ is the two-photon detuning in atoms. The detuning $\delta=\Delta_1+\Delta_2+\Delta_0$ is the detuning in the overall process. Note that the validity of Eq. (1) requires

$$\frac{\mu_{1A}E_0}{\Delta_1},\frac{\mu_{2A}E_0}{\Delta_2},\frac{\mu_{2A}E_0}{|\Delta_1+\Delta_2|},\frac{V_2}{\Delta_0}=\frac{\hbar}{4\pi\epsilon_0}\frac{\mu_{2A}\mu_{1B}}{R^3\Delta_0}\ll 1 .$$

Now we consider the case where both atoms are coherently driven by the electromagnetic field as shown in Fig. 4(a) (two-atom system). The state vector of the system is taken to be of the form

$$\begin{aligned}\psi(t)=&|0a\rangle|0b\rangle a_0(t)+|0a\rangle|1b\rangle\exp(i\omega_3t)a_1(t)\\&+|1a\rangle|0b\rangle\exp(i\omega_1t)a_2(t)\\&+|2a\rangle|0b\rangle\exp[i(\omega_1+\omega_2)t]a_2'(t)\\&+|1a\rangle|1b\rangle\exp[i(\omega_1+\omega_3)t]a_3(t) .\end{aligned}$$

In the process, the initial state $|0a\rangle|0b\rangle$ is virtually excited by the electromagnetic field to the state $|0a\rangle|1b\rangle$. A virtual collision then transfers the excitation from $|0a\rangle|1b\rangle$ to the state $|1a\rangle|0b\rangle$ which in turn gets virtually excited by the electromagnetic field to $|2a\rangle|0b\rangle$. Finally a collisional transfer from $|2a\rangle|0b\rangle$ to $|1a\rangle|1b\rangle$ nearly conserves the overall energy for the transition [Fig. 4(b)]. The time-dependent Schrödinger equation gives the following coupled equations for the time-dependent coefficients:

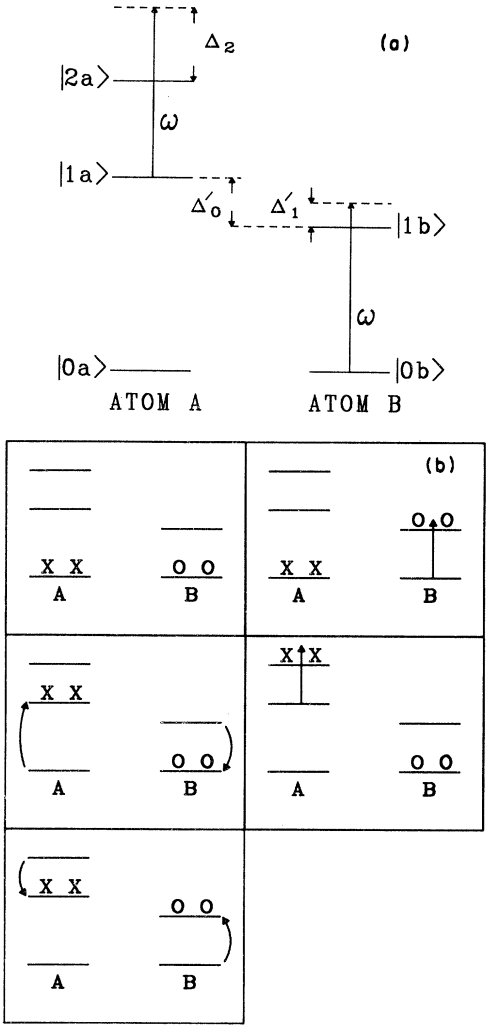

FIG. 4. (a) Partial energy-level diagram showing the relevant levels, transitions, and detunings for the two-atom case. In this case the field simultaneously excites atoms A and B directly. (b) Set of simplified energy levels showing the sequence of interactions for the case of both atoms interacting with the field.

$$\frac{da_0}{dt}=i\mu_{1B}E_0\exp(i\Delta_1't)a_1 ,$$

$$\frac{da_1}{dt}=i\mu_{1B}^*E_0\exp(-i\Delta_1't)a_0+iV_1\exp(-i\Delta_0't)a_2 ,$$

$$\frac{da_2}{dt}=iV_1^*\exp(i\Delta_0't)a_1+i\mu_{2A}E_0\exp(i\Delta_2t)a_2' ,$$

$$\frac{da_2'}{dt}=i\mu_{2A}^*E_0\exp(-i\Delta_2t)a_2+iV_2\exp(-i\Delta_0t)a_3 ,$$

$$\frac{da_3}{dt}=iV_2^*\exp(i\Delta_0t)a_2' ,$$

where

$$\Delta_1'=\omega_3-\omega,\quad \Delta_0'=\omega_3-\omega_1,$$

$$\Delta_2=\omega_2-\omega,\quad \Delta_0=\omega_2-\omega_3,$$

$$\mu_{1B}=\langle 0b\,|\,\hat{\mu}_{BZ}\,|\,1b\rangle/\hbar,\quad \mu_{2A}=\langle 1a\,|\,\hat{\mu}_{AZ}\,|\,2a\rangle/\hbar,$$

$$V_1=\langle 0b\,|\,\langle 1a\,|\,\hat{V}_{ABZ}\,|\,0a\rangle\,|\,1b\rangle/\hbar,$$

$$V_2=\langle 1a\,|\,\langle 1b\,|\,\hat{V}_{ABZ}\,|\,0b\rangle\,|\,2a\rangle/\hbar.$$

In contrast to the one-atom case, the electromagnetic field here excites a coherent superposition of states of atoms A and B. This system of five coupled levels can be reduced again using the adiabatic approximation to an effective two-level system comprised of the initial and final states of amplitudes a_0 and a_3, respectively:

$$\frac{da_0}{dt}+iS_1a_0=C_0E_0^2V_1V_2\exp(i\delta t)a_3 \tag{6}$$

and

$$\frac{da_3}{dt}+iS_2a_3=C_4E_0^2V_1^*V_2^*\exp(-i\delta t)a_0, \tag{7}$$

with

$$S_1=b_1E_0^2+b_2E_0^2V_1^2+b_3E_0^4V_1^2,\quad S_2=b_4V_2^2,$$

where $\delta=\Delta_1+\Delta_2-\Delta_0-\Delta_0'$ is the detuning from exact resonance and the coefficients b_i and c_i depend on the various detunings and the dipole-moment matrix elements.

It is to be noted that the ground state is Stark shifted by the amount $b_1E_0^2$, and also shifted by a new type of shift $b_2E_0^2V_1^2+b_3E_0^4V_1^2$. The final state, on the other hand, is only collisionally shifted in this model by an amount $b_4V_2^2$. Figure 5 shows a schematic of the interatomic potential in this case. Unlike the previous case, the lower level is now curved as well. This additional shift depends on intensity and can therefore be adjusted so that the two levels remain parallel even at small R. The transition probability, when the atoms interact via the dipole-dipole interaction is[1]

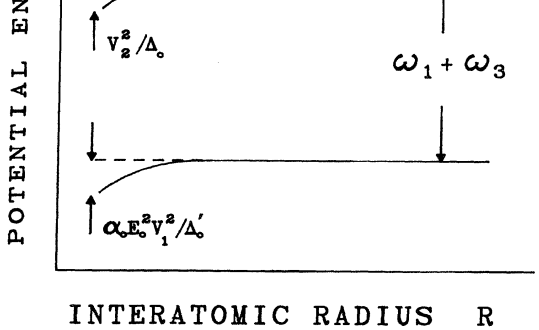

FIG. 5. Schematic of the interatomic potential as a function of R, the internuclear distance, for the two-atom case.

$$|a_3(\infty)|^2=4\alpha'^2E_0^4\left|\int_0^\infty R^{-6}\cos\left[\int_0^t(C'R^{-6}-\delta)dt\right]dt\right|^2, \tag{8}$$

$$\alpha'=\frac{\hbar^2\mu_{1B}^2}{\Delta_1'}\alpha, \tag{9}$$

$$C'=\hbar^2\mu_{2A}^2\mu_{1B}^2/\Delta_0-\hbar^2\alpha_0E_0^2\mu_{1B}^2\mu_{1A}^2/\Delta_0', \tag{10}$$

$$\alpha_0=\mu_{1B}^2/\Delta_1'(\Delta_0'-\Delta_1'). \tag{11}$$

Note that the validity of Eqs. (6) and (7) requires in addition to the above conditions

$$\frac{\mu_{1B}E_0}{\Delta_1'},\frac{V_1}{\Delta_0'}=\frac{\hbar}{4\pi\epsilon_0}\frac{\mu_{1A}\mu_{1B}}{R^3\Delta_0'},\frac{V_1}{\Delta_1},\frac{V_1^2}{\Delta_0'\,|\,\Delta_0'-\Delta_1'\,|},\frac{V_2^2}{\Delta_0\Delta_2}\ll 1.$$

The cross sections for the two processes are derived from $|a_3(\infty)|^2$ by integrating over the impact parameter $\sigma=2\pi\int|a_3|^2\rho d\rho$. The above expressions for $|a_3(\infty)|^2$ were numerically integrated using cautious adaptive Romberg extrapolation. Since it is necessary to integrate over time and square the result before integrating over impact parameter, two versions of a one-dimensional working algorithm, though common, were employed. The computes codes were part of a library leased from IMSL, Inc. No attempt was made to average over a thermal velocity distribution as this would have greatly increased cost and would not have altered the basic physics. Previous workers analyzing a one-photon radiative collision in this approximation have shown that the maximum cross section is underestimated by about 50%.[6]

Although we have used a one-frequency source in the derivation of the effect, one can easily show that the same expressions are valid in the case of a two-frequency source of fixed phase difference provided that the wavelengths are sufficiently different. In our numerical calculations we have used a two-frequency interaction because it allows more freedom in choosing realistic conditions.

In the numerical calculations we took the following values: $\mu_{1A}=1.25$ a.u., $\mu_{2A}=0.25$ a.u., $\mu_{1B}=5$ a.u., $\Delta_0'=-6000$ cm^{-1}, $\Delta_1=5000$ cm^{-1}, and $\Delta_2=-9000$ cm^{-1}. With these numerical values, the quantity C' goes to zero at laser intensity $I_0=4.34$ GW/cm^2. Despite the rather sizable value of intensity, the quantity $(\mu_{2A}/\mu_{1A})^2(\Delta_0'/\Delta_0)=0.03$. It is this parameter which measures the validity of the weak-field limit approximation and which we require to be $\ll 1$.

We start by describing the results of the one-atom case. The intensity dependence of the response enters only through the factor E_0^4 which gives a quadratic dependence on the intensity. This factor results from the two-photon nature of the process. The absolute line shape is shown in Fig. 6. The peak of the response occurs at $\delta=0$, that is, when the atoms are at infinite internuclear separations.[3–5,7,8]

We now describe the results of the two-atom case. In this case the intensity dependence is far more involved. Figures 7(a)–7(e) give the line shape of the two-collision

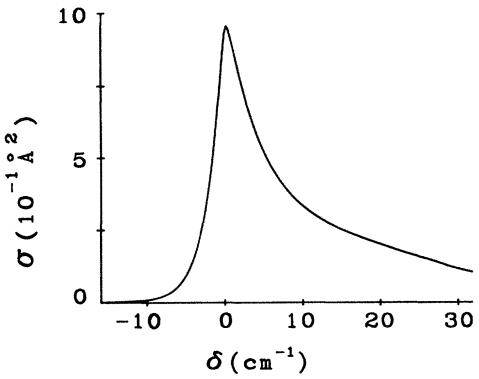

FIG. 6. Line shape of the one-atom case, at laser intensity $I=4.34$ GW/cm^2.

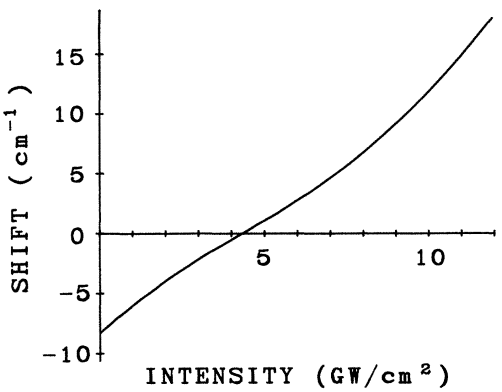

FIG. 8. Line shift as a function of the laser intensity in the two-atom case.

case at laser intensities 1.02, 1.87, 2.68, 4.34, and 8.84 GW/cm^2, respectively. These figures show that as the intensity rises from 1.02 GW/cm^2, the asymmetry on the red wing becomes less pronounced. At intensity $I_0=4.34$ GW/cm^2 the line shape becomes completely symmetric indicating what we call intensity-induced symmetry (phase resonance). As the intensity rises to a value above the intensity that produces the phase resonance, the line shape becomes again asymmetric, developing a blue wing.

It is to be noted that the line shape exhibits a shift as the intensity of the radiation is varied. The shift of the peak of the response is plotted as a function of intensity in Fig. 8 for values around the value I_0 (at phase resonance). The shift is found to be linear at small intensities and also linear in the neighborhood of I_0. At intensities larger than I_0, the shift becomes a nonlinear function of the intensity. Only at phase resonance does the response peak at $\delta=0$, that is, occurs when the atoms are at infinite internuclear separations (R_∞). At intensities different from I_0, the resonance occurs at $\delta\neq 0$, that is, at finite internuclear separations.

The cross section of the two-collision case was also studied as a function of the intensity of the laser. The peak of the absolute cross section is shown in Fig. 9. At higher intensities the cross section continues to rise, while at lower intensities, the cross section vanishes. Figure 10 gives the peak of the intensity-normalized cross section σ_0/I^2 as a function of intensity in the neighborhood of I_0. It shows that the cross section exhibits the phase resonance. Below $I=1.3\times 10^7$ W/cm^2 the normalized cross section approaches a constant value as the intensity decreases, while above $I=6\times 10^9$ W/cm^2, the cross section continues to decrease as the intensity increases. Finally, Fig. 11 gives the ratio of the peak of the cross section for the two-atom case at phase resonance to that of the one-atom case as a function of the minimum impact parameter. The figure shows the enhancement resulting from the interaction at small impact parameters due to the phase resonance. This can be understood by recalling that the one-collision case suffers dephasing such that collisions occurring at impact parameters less than the well-known Weisskopf radius do not contribute to the cross section. For the constants used in our example, this quantity is calculated to be 6.2 Å. For the two-atom case, this de-

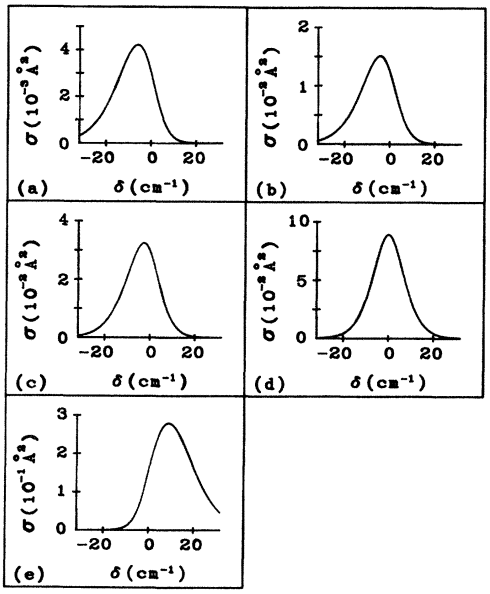

FIG. 7. Line shape of the two-atom case at laser intensities, (a) 1.02 GW/cm^2, (b) 1.87 GW/cm^2, (c) 2.68 GW/cm^2, (d) 4.34 GW/cm^2, (e) 8.84 GW/cm^2.

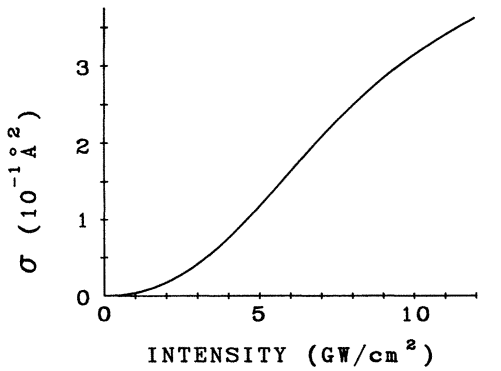

FIG. 9. Peak of the cross section as a function of the laser intensity for the two-atom case.

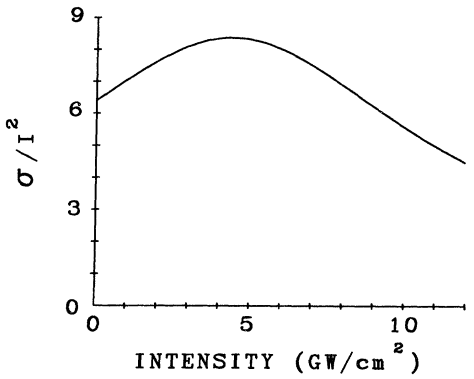

FIG. 10. Intensity-normalized peak of the cross section σ_0/I^2 plotted as a function of intensity for the two-atom case showing the phase-resonance effect.

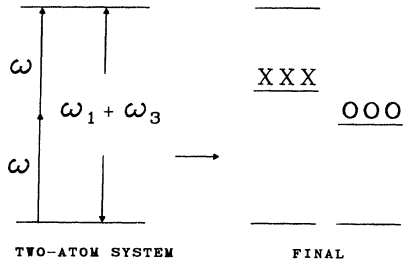

FIG. 12. Schematic of the coherent two-atom system (at phase resonance) showing the effective relevant energy levels. The interatomic potentials of the initial and final states are parallel, thus allowing a single-frequency radiation to interact with it over a wide range of interatomic distances. The absorption of the system occurs at $\omega=(\omega_1+\omega_3)/2$.

phasing is effectively canceled when phase resonance is achieved allowing smaller impact parameters to contribute to the cross section. The result is the dramatic increase, shown in Fig. 11, in the ratio of the two cross sections when the integration over impact parameters includes the region closer than 6 Å.

The results of the two-atom case can also be understood by examining the energy nonconserving nature of some of the interactions. When energy nonconserving steps are involved in atomic interactions, energy shifts in the participating energy levels occur. The familiar ac Stark shift introduced in two-photon interactions of an electromagnetic field with a three-level system with a nonresonant intermediate state is one example of these energy nonconserving effects. The van der Waals energy shift is another example of these effects where two atoms interact through their long-range dipole-dipole interaction via an energy nonconserving process.

In the present process we have both effects: energy nonconserving electromagnetic interactions and energy nonconserving collisional interactions occurring simultaneously in one sequence. As a result, a mixed intensity-induced collisional shift is introduced. This shift is equivalent to a van der Waals shift with an intensity modulated C_6. In Eq. (8), C' is an intensity modulated C_6 for the present process.

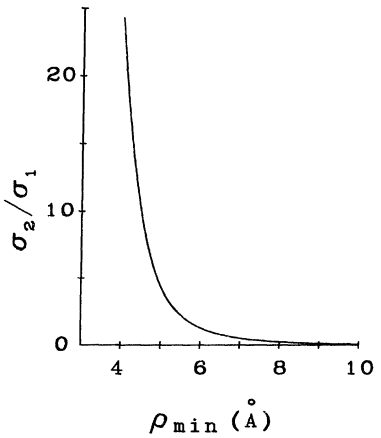

FIG. 11. Peak of the cross section for the two-atom case (at phase resonance) divided by that of the one-atom case as a function of the minimum impact parameter used in the calculation.

The phase of the final scattering state relative to the initial scattering state is the argument of the cosine in Eq. (8). The phase difference at $R=\infty$ is δt which is controlled by the frequency of the laser excitation. At finite R, the phase is further controlled by the laser intensity, i.e., by controlling C'. By choosing the detunings appearing in C' appropriately, the intensity-induced shift can be chosen to have the opposite sign of the pure collisional shift, allowing for possible cancellation. Finally, for laser pulses which change very little during the collision (i.e., long pulses compared to the time of collision) complete cancellation of the collisional shift can be achieved by choosing the appropriate laser intensity, thus achieving phase resonance for all internuclear separations and, hence, all times.

In the above numerical example, C' becomes zero at laser intensity $I_0=4.34$ GW/cm^2. This is the intensity at which phase resonance occurs. The situation where C' is very small suggests a large coupling coefficient in the absence of any dephasing effect for all internuclear separations. This leads to large cross sections for the process. Moreover, because of the absence of the shift, the line shape is expected to be symmetric. However, because of detuning at small R, orbiting phenomena play a significant role, thus making the calculation very hard at small nuclear separation. In the above numerical example we restricted $R \geq 4.5$ Å such that orbiting may not play an important role. Additional contribution to the cross section from $R \leq 4.5$ Å are expected to arise in the neighborhood of phase resonance, thus making the present calculation a lower limit for the cross section of the phase resonance.

We now discuss the line shift encountered in the two-collision case. In the one-atom dipole-dipole interaction, the collisional coupling has a radial dependence of the form R^{-3}. It is known that such an interaction, when accompanied by the radial dependence of the dephasing of the form R^{-6}, results in a response peaked at $\delta=0$, that is, when the atoms are at infinite internuclear separations.[8] The departure from R^{-3} makes the position of the peak

occur at $\delta \neq 0$. This property was previously noted[7] in charge-exchange processes where the interaction is of the form R^{-4}. Moreover, it is expected that the position of the peak will be dependent on the magnitude of the dephasing, that is, on C_6. Since, in the two-collision case, the interaction is of the form R^{-6} and the dephasing is dependent on the intensity, we expect the line to shift as a function of intensity.

In conclusion we state that the present effect occurs only when both partners of the system are simultaneously driven by the field [Fig. 1(b)]. The nature of the phenomenon lies in the fact that the system in Fig. 1(b) undergoes energy nonconserving sequences of radiative and collisional interactions which result in the familiar ac Stark shift and collisional shift and in a new mixed ac Stark-collisional shift. Whereas the familiar collisional shift is responsible for the dephasing of the coherence, the new mixed shift can be used to eliminate this dephasing effect for a wide range of internuclear distances (phase resonance) if the intensity of the radiation and other detunings are chosen appropriately.

When phase resonance is achieved, the transition frequency of the system which is ordinarily dependent on the internuclear distance relevant to the process becomes constant (parallel potential curves) and, consequently, the two-atom system may then interact coherently with the electromagnetic field without interruption (see Fig. 12). It is found that such coherent interaction will result in the excitation of the relevant transitions of the individual atoms of the two-atom system at frequencies ω_1 and ω_3 if the frequency of the excitation ω is in near resonance with half the frequency of the two-atom system $(\omega_1+\omega_3)/2$. Our results also indicate that the coherent absorption by the coherent two-atom system will dominate the absorption by the incoherent one-atom system of Fig. 1(a).

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