Observation of transparency and population trapping due to atomic coherent effects

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The electromagnetically induced transparency in a V-shaped atomic system is observed by a spectroscopy technique. The experimental results show that the absorption coefficient at maximum coherence is reduced by about 72% of the maximum absorption α_0, which is the case without the coherent effect. Meanwhile we also observed indirectly population trapping in the two excited states, which means that there is no decay via spontaneous or stimulated emission to the lower state.

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Recently there has been considerable interest in the quantum interference effects [1–15], which play an important role in an atomic system affecting the emission and absorption spectra. Many interesting phenomena depend on these interference effects, for example, laser without inversion, electromagnetically induced transparency, and refractive index enhancement [1,2,16]. To obtain these effects a coherence between the levels must be established, possibly by microwaves resonant with the level transition or via initial preparation or by Raman interaction [2,4]. It is well known that maximum two-photon coherence leads to population trapping in Λ-shaped three-level systems interacting with resonant laser fields [9,10]. The population is equally trapped in the two lower levels due to optical pumping of the ground-state sublevels into a coherent superposition state. Under this condition, the atom is decoupled from the laser fields. This effect was observed nearly twenty years ago in an optical pumping experiment by Alzetta *et al.* [10] and in an atomic beam experiment by Gray, Whitley, and Stroud [16]. For the V-shaped three-level system Cohen-Tannouodji and Reynaud [17] and Scully and Zhu [2] suggested that an effect similar to coherent population trapping should be expected. Boublil, Wilson-Gordon, and Fridmann have theoretically studied the interaction of a closed V-shaped three-level system with two laser fields having arbitrary intensities [18]. They show that at sufficiently high intensity and exact resonance, half the population should be in the ground state and half in the coherent superposition of the two upper states. In this case, strong coherence reduces the stimulated emission and almost cancels the one-photon absorption, and the absorption medium becomes transparent [2,18]. In one recent report, Boller, Imamoglu, and Harris have observed a transparency effect in a Λ-shaped level system by interference between two dressed states [19]. For the V configuration a resonant saturation spectroscopy in fast accelerated atoms beam of Ne* and Ca* had been carried out. However, the transparency effect due to coherent quantum interference was not reported [20].

In this paper we report an experimental observation of electromagnetically induced transparency of the medium and population trapping due to atomic coherent interference in the V-shaped level system. In this experiment, sodium vapor is used as an absorptive medium. We note that sodium is not a good three-level atom because of the ground-state hyperfine splitting. This fact may have important consequences in the experiment, because, at high intensity of the light field, optical pumping in the ground state is significant. If this is the case, then the two-photon coherence has little to do with the experimental observation. However, if the two upper states are prepared in a coherent superposition, then the population of the upper levels undergoes no spontaneous or stimulated radiative decay; therefore, the optical pumping becomes insignificant [2]. In this paper we report an experimental observation of transparency and an indirect evidence of population trapping in the excited states due to atomic coherent effects.

As shown in Fig. 1, if the atoms are moving with velocity V in a standing-wave field and the laser frequency ω_l is tuned to a frequency ω_0, which is exactly halfway between the $|2\rangle$ and $|3\rangle$ states. Here $\omega_0=(\omega_1+\omega_2)/2$, and ω_1 and ω_2 are two atomic transitions. Since the standing wave consists of two counterpropagating waves E^+ and E^-, and moving atoms have a velocity component V_z along the traveling waves, the frequencies of the traveling waves E^+ and E^- are Doppler shifted by an amount $\pm KV_z$ to resonate with the two atomic transitions of $|1\rangle$ to $|2\rangle$ and $|1\rangle$ to $|3\rangle$. In this case both counterpropagating traveling waves interact with one of the two groups of atoms having $Vz=\pm c(\omega_1-\omega_2)/2\omega_0$ via the two atomic transitions, as shown in Fig. 1. Subsequently, the two traveling waves

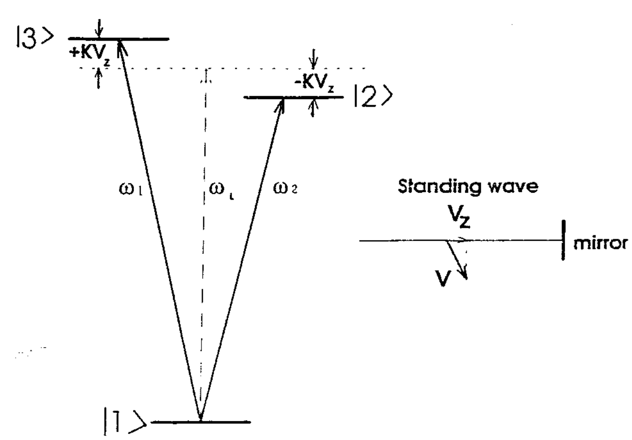

FIG. 1. Partial energy-level diagram of sodium (not to scale) and an atom moving in a standing wave.

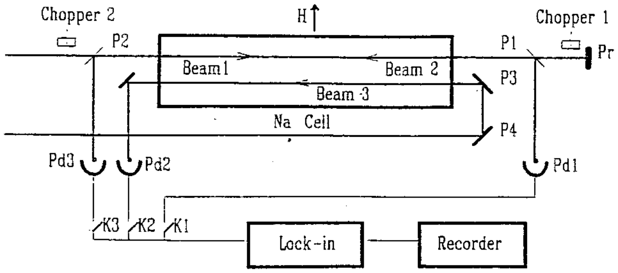

FIG. 2. Experimental scheme. Beams 1 and 2 are used for the transparency experiment, beam 3 is used for the population trapping experiment.

couple the two different upper states to a common lower state $|1\rangle$; the coherence between $|2\rangle$ and $|3\rangle$ is established by the strong coherent traveling waves of frequencies ω_1 and ω_2. The external fields change the absorption profiles from those of bare atoms, leading to the possibility of reduction of absorption of the medium. According to theoretical calculations, the induced polarization at frequencies ω_1 and ω_2 is given by $P_1(\omega_1)=d_{31}\rho_{31}$ and $P_2(\omega_2)=d_{21}\rho_{21}$. Here, d_{31} and d_{21} are dipole moments, and ρ_{31} and ρ_{21} are off-diagonal density matrix elements, respectively. The one-photon absorption is proportional to $\mathrm{Im}\rho_{31}$ and $\mathrm{Im}\rho_{21}$, which are given as [18]

$$\rho_{21}=-\frac{\Omega_1(\rho_{22}-\rho_{11})}{2[\Delta_1-i(1/T_2)_{21}]}-\frac{\Omega_2\rho_{23}}{2[\Delta_1-i(1/T_2)_{21}]}, \quad (1)$$

$$\rho_{31}=-\frac{\Omega_2(\rho_{33}-\rho_{11})}{2[\Delta_2-i(1/T_2)_{31}]}-\frac{\Omega_1\rho_{32}}{2[\Delta_2-i(1/T_2)_{31}]}. \quad (2)$$

Here Ω_1 and Ω_2 are the one-photon Rabi frequencies, Δ_1 and Δ_2 are the one-photon detuning, $(1/T)_{ij}$ are the dephasing rates for the off-diagonal density matrix elements, and ρ_{23} and ρ_{32} express the coherence between $|2\rangle$ and $|3\rangle$. For exact resonance and large equal Rabi frequencies, there is almost complete cancellation between the two terms that contribute to ρ_{21} and ρ_{31}, so the medium becomes nonabsorptive [2,18].

We first describe the experiment to confirm the existence of transparency of the medium induced by the atomic coherence effects. We use a standard saturation spectroscopy technique [21], as shown in Fig. 2, to detect the transparency. A cell containing sodium vapor is placed in a laser standing wave, in which the sodium vapor pressure is kept low enough by a temperature-controlled heater. The cell temperature is about 150 °C, and the mean free path of the sodium atoms in considerably longer than the dimension of the cell, so that atoms do not suffer from collision effects. The cell, a Pyrex cylinder 2.5 cm in diameter and 25 cm long, is located at the center of the three pairs of Helmholtz coils and a magnetic field of 1.7 G is perpendicular to the cylinder axis Z. The two counterpropagating waves E^+ and E^- pass through the cell, one of which is used as a pumping beam and chopped by chopper 1 (chopper 2 is open); the other one is used as a probe beam to monitor the variation of the laser transmission through the sodium vapor. A coherent 699-21 frequency-stabilized dye laser is tuned to the sodium D_1 line resonance. The laser beam of TEM_{∞} mode radiation of intensity 5 mW/cm^2 is directed along the Z axis and retroreflected by a mirror Pr. The laser beam is 3 mm in diameter and circularly polarized. Two glass plates, $P1$ and $P2$, are inserted into the path of the standing wave, and part of the traveling waves, about 3%, is reflected out from the beam by the glass plates, which are used for detection. A phase-sensitive detection technique is used to measure the transparency of the sodium vapor.

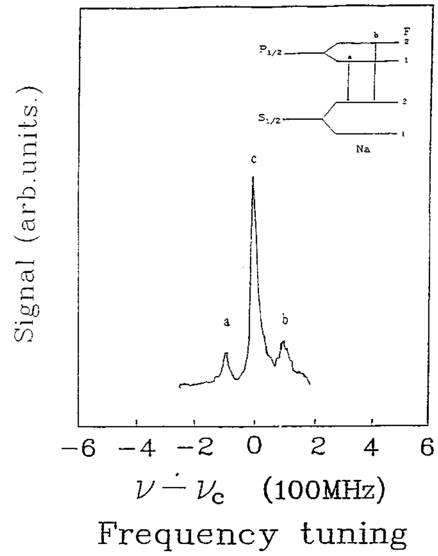

FIG. 3. Saturation spectrum of D_1 hyperfine structure of atomic sodium in a circular polarized laser standing-wave field. The peaks labeled a and b correspond to the transitions in the inset. Peak c is due to atomic coherence effects when the laser is tuned to exactly halfway between the transition a and transition b.

The presence of the coherent interference effect is evident in the saturation spectrum of the D_1 hyperfine structure of the sodium atom, as shown in Fig. 3. The spectrum is recorded by the photodetector Pd_1 to show the transparency effects of the medium. The left and right peaks a,b arise from the $3S_{1/2}$, $F=2$ to $3P_{1/2}$, $F=1$ and $3S_{1/2}$, $F=2$ to $3P_{1/2}$, $F=2$ transitions, respectively. In this case both traveling waves are resonant with one velocity group of atoms having a component $V_z=0$ in the direction of the standing wave; this means that the atoms are moving perpendicular to both traveling waves. The central peak indicates the atomic coherent effects, which happen only when the laser is tuned to exactly halfway between ω_1 and ω_2, as indicated above. It clearly shows that the peak induced by the atomic coherence of the upper levels is much higher than the neighboring peaks of the saturation spectrum. It is known that in the weak standing wave the coherent interference of the states is negligible; the amplitude of peak a is proportional to $|d_{12}|^4$, peak b is proportional to $|d_{13}|^4$, and the central peak is proportional to $|d_{12}|^2|d_{13}|^2$ [22,23]. For the transitions of $3S_{1/2}$, $F=2$ to $3P_{1/2}$, $F=1$ and $3S_{1/2}$, $F=2$ to $3P_{1/2}$, $F=2$, we have $|d_{21}|\approx|d_{13}|$. Therefore, the three peaks have similar amplitudes [20]. However, in the strong standing-wave field, the Rabi frequency $\Omega_1=\Omega_2=6.5$ MHz, the strong coherent effect leads to cancellation of the one-photon absorption. The central peak is seven times higher than its neighbors, as shown in Fig. 3. We have also measured the Doppler absorption profile of the sodium vapor. The maximum absorption coefficient is about $\alpha_0=1.49\times10^{-1}$

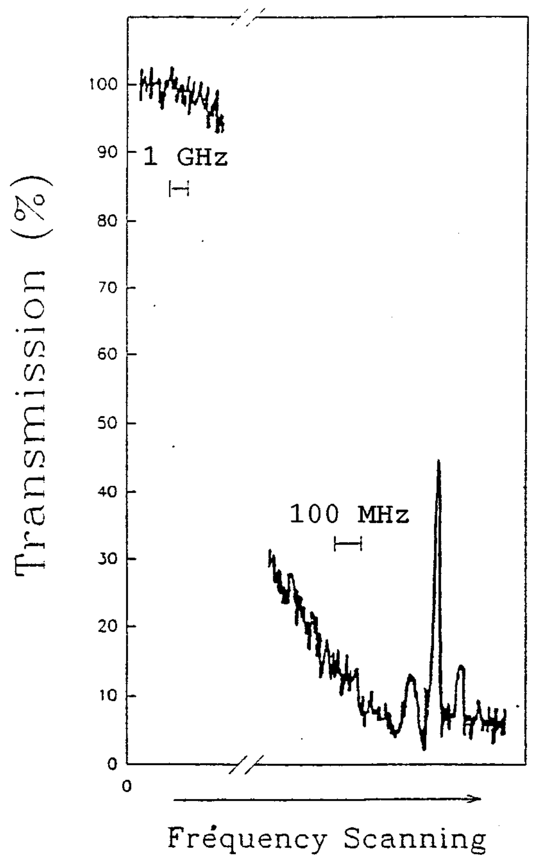

FIG. 4. Transmission of probe laser versus probe detuning for the D_1 line of the sodium atom.

cm^{-1}. When the coherence between $|2\rangle$ and $|3\rangle$ is established by the strong field, the center peak increases sharply (see Fig. 4). By measuring the depth of this dip, we obtain an absorption coefficient $\alpha_c = 4.11\times 10^{-2}$ cm^{-1}, which is reduced by about 72% of the maximum absorption α_0 without atomic coherence. In this experiment we have found that the effect of atomic coherent interference is very sensitive to the direction and intensity of the magnetic field. The maximum transparency is observed when the direction of the magnetic field is perpendicular to the propagating direction of the laser beam, which is the axis of quantization. The magnetic field will cause a mixing of all Zeeman sublevels M_F of a particular hyperfine state F. As a result, all sublevels are involved in the coherent interaction with the light. The sodium atom is rather similar to the closed V-shaped three-level system; increase of the magnetic field does not destroy the atomic coherence of the upper states.

We now describe the experiment to observe the population trapping in the two excited states due to atomic coherence effects. According to the theoretical calculation, as the atoms are initially in the ground level $|1\rangle$

$$\rho_{11}^0 = 1 \quad \rho_{22}^0 = \rho_{33}^0 = 0, \tag{3}$$

when the time tends to infinity, we find that

$$\rho_{11}(t) = \tfrac{1}{2} \quad \rho_{22}(t) = \rho_{33}(t) = \tfrac{1}{4}, \tag{4}$$

which is not a function of time. The population is therefore trapped in the upper levels and the atoms will not decay to the lower level via spontaneous or stimulated emission. To confirm this, we have measured indirectly the population distribution of atoms in the ground state. The experimental scheme is shown also in Fig. 2; here we added a probe beam 3, which is propagating in the direction of the standing wave but separated from it by 6 mm, to detect the changes of population distribution in the state $3S_{1/2}$, $F=2$. Probe beam 3 comes from the same Coherent Laser 699-21 laser and has the same frequency as beams 1 and 2. In the low-pressure cell, if laser beam 1 creates a hole in the velocity distribution of the atomic population, then according to the principle of saturation spectroscopy technique the hole can be detected by probe beam 3 [24]. In this experiment, first we take off the mirror Pr; beams 1 and 3 become two counterpropagating waves. When the laser frequency ω_l is tuned to exactly halfway between the $|2\rangle$ and $|3\rangle$ states, beam 1 creates two holes on the population distribution of the ground state by optical pumping. If beam 1 is modulated by chopper 2 (chopper 1 is open), the probe beam detects a hole as a peak in the spectrum and it is two times larger than the neighboring peaks. Figure 5(a) shows the detected absorption spectrum from Pd3 by probe beam 3, which indicates the burned holes by optical pumping effects [24]. Now we put the mirror Pr back into beam 1, which is retroreflected to form a standing wave in our transparency experiment, but the probe beam is not changed. The detected spectrum by probe beam 3 is shown in Fig. 5(b). It shows that the center peak in the standing wave is smaller than that in the traveling wave at crossover resonance. If the optical pumping effect is the dominant effect in the standing wave, then the center peak should be larger than the peak in the traveling wave, because the field intensity of the standing wave is twice as strong as that of the traveling wave. However, comparing the two center peaks in Figs. 5(a) and 5(b), the hole burned in the standing wave is much smaller than the hole burned by optical pumping in the traveling wave. The reduction of the center peak in the standing wave is due to atomic coherence effects. In this case the

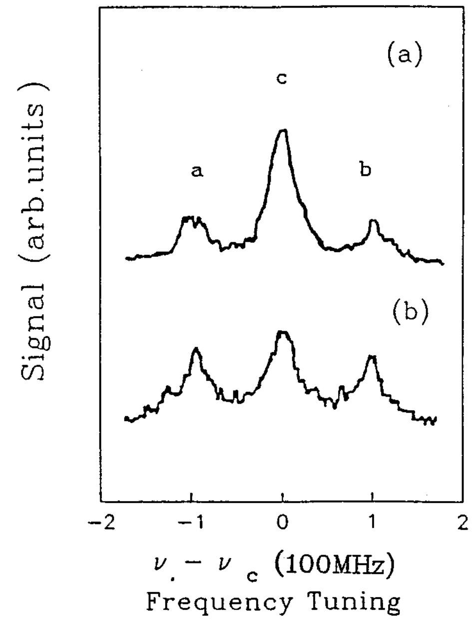

FIG. 5. Absorption spectrum of D_1 hyperfine structure of atomic sodium detected by probe beam 3 (see text).

population in the upper levels is trapped and will not decay to the lower levels via spontaneous or stimulated emission; only when the atoms go out from the standing wave, where atomic coherence effects no longer exist, will the spontaneous emission take place and part of the atoms can decay to the $3S_{1/2}$, $F=1$ state. Therefore, the smaller hole burned in the standing wave is due to coherent population trapping.

In conclusion, we find that it is possible to establish atomic coherence between the upper levels of the V-shaped configuration by a coherent standing wave. Under this condition, when the stimulated emission is reduced and the population of atoms is trapped in the excited states, the medium becomes transparent. We also found that the atomic coherence effect is very sensitive to the external magnetic field; the maximum transparency is observed when the direction of the magnetic field is perpendicular to the propagating direction of the laser beam. It is known that sodium is a natural candidate for experiments of laser without inversion, electromagnetically induced transparency, and refractive index enhancement [1,2,16]; therefore, it may be possible to observe some basic features of these effects by means of the principle demonstrated in our experiment.

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