Multilevel dark states in an inhomogeneously broadened open atomic system

Yifu Zhu, Shijun Wang, and Neil M. Mulchan
Department of Physics, Florida International University, Miami, Florida 33199
(Received 29 October 1998)

We report an experimental observation of coherent population trapping in multilevel dark states prepared in the ground hyperfine states of ^{87}Rb atoms confined in a room-temperature vapor cell. The dark states are created by a linearly polarized coupling laser that is tuned to the ^{87}Rb D_1 $F=2\leftrightarrow F'=1$ or 2 transition and establishes Λ-type transition chains. The Doppler shift for the Λ-type transition chains is compensated by the left and right circularly polarized components of the coupling laser. The multilevel dark states that consist of three or two magnetic sublevels among the five degenerate magnetic sublevels in the $F=2$ ground hyperfine state are probed by a weak probe laser scanned across the same D_1 transition and their existence is manifested by a strong dependence of the probe excitation on the probe polarization. Our experiment demonstrates the importance of coherent population trapping in a laser coupled degenerate multilevel open atomic system, which may play an important role in diverse physical phenomena such as atom cooling and trapping, optical pumping, and multiple laser excitation and ionization of atoms and molecules. [S1050-2947(99)05505-5]

PACS number(s): 42.50.Gy, 42.50.Hz, 32.80.Bx

I. INTRODUCTION

Coherent population trapping (CPT) relies on the formation of a coherent superposition of ground or metastable states that are decoupled from the incident electromagnetic field and, hence, referred to as dark states [1]. CPT was originally observed in closed three-level Λ systems in which a dark state composed of a coherent superposition of the two ground states is generated by two radiation fields [2,3]. The two quantum interaction paths between the dark state and the excited state interfere destructively and the atoms in the dark state cannot be excited by the fields that generate the dark state. CPT plays an important role in a variety of physical phenomena involving radiation matter interactions, such as cooling of atoms below the photon recoil limit [4,5], trapping of atoms in optical lattices [6,7], electromagnetically induced transparency (EIT) [8–10], lasing without population inversion [11–13], and control of nonlinear atomic polarizabilities [14–16]. Studies of these phenomena have all been based on closed three-level atomic systems in which total atomic population is conserved.

In practical atomic systems, atomic transitions often involve magnetic sublevel structures that can lead to interesting consequences. Coherent radiation-atom interaction in multilevel degenerate systems has received increasing attention in recent years [17–19]. It has been found that CPT is a more general phenomenon that exists in a two-state atomic system with degenerate multiple ground and excited sublevels. Interaction of a degenerate multilevel system with an elliptically polarized coupling field produces atom-field dressed states. When the number of degenerate ground-state sublevels is greater than or equal to the number of degenerate excited-state sublevels, the dressed states can be divided into bright dressed states that consist of a coherent mixture of both the ground and excited sublevels, and dark states that consist of the ground sublevels only. The bright dressed states are shifted in energy by the field-atom interaction while the energy of the dark states is not shifted. The dark states produced by the coupling laser are decoupled from the same coupling laser and CPT is therefore realized in a degenerate multilevel system [19,20]. In open multilevel atomic systems (such as D_1 and D_2 transitions in alkali-metal atoms), optical pumping transfers atomic population from one ground hyperfine state to the other noninteracting hyperfine state, which is detrimental to the multilevel CPT. Theoretical studies in homogeneous atomic systems show that the multilevel CPT competes effectively with the optical pumping and can be preserved in an open atomic system [20]. Specifically, Ling *et al.* showed theoretically that CPT exists in the open multilevel Rb D_1 $F=2\leftrightarrow F=1$ transitions [21]. Recently, Milner and Prior demonstrated experimentally the multilevel CPT on the D_1 $F=2\leftrightarrow F'=2$ transitions of sodium atoms in an atomic beam apparatus [22].

In a Doppler-broadened atomic system, atoms with different thermal velocities experience different frequency detunings from the coupling laser. But the two circular components of a linearly polarized coupling laser that couple the $\Delta m=1$ and $\Delta m=-1$ sublevel transitions separately have exactly the same Doppler shift, the net effect being a complete cancellation of the Doppler shifts for Λ-type transitions induced by the two circular components of the same coupling laser (see Fig. 1). The Λ-type coupling of the degenerate hyperfine ground sublevels produces dark states. Although atoms with different thermal velocities experience different frequency detunings from the coupling laser, the Λ-type coupling is Doppler-free and resonant for all atoms. Therefore, coherent population trapping in a Doppler-broadened, open multilevel system should be robust and readily observable just like CPT in a homogeneous, open multilevel atomic system. Below, we analyze the multilevel dark states created by a resonant coupling laser in the D_1 transitions of ^{87}Rb atoms and report an experimental observation of CPT in Doppler-broadened, open multilevel atomic systems consisting of ^{87}Rb atoms confined in a room-temperature vapor cell.

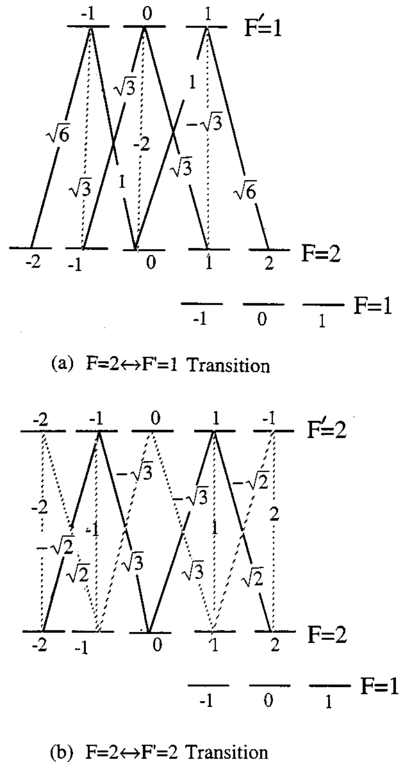

FIG. 1. Energy levels and relative dipole moments for the ^{87}Rb D_1 $F=2\leftrightarrow F'=1$ transition and $F=2\leftrightarrow F'=2$ transition. The left and right circular polarization components of a linearly polarized coupling laser induce $\Delta m=+1$ and $\Delta m=-1$ transitions, respectively. This establishes Λ-type coupling chains (shown by solid lines) and generates dark states, which causes coherent population trapping in a degenerate multilevel system.

II. DARK STATES IN THE ^{87}Rb D_1 TRANSITIONS

Consider the ^{87}Rb D_1 $F=2\leftrightarrow F'=1$ and $F=2\leftrightarrow F'=2$ transitions with relevant energy levels, links of the transitions among magnetic sublevels, and the coupling constants (dipole moments) depicted in Fig. 1. Atoms in the excited state can spontaneously decay to the hyperfine ground state $F=1$, which makes the two degenerate multilevel systems open. A coupling laser linearly polarized in the x direction (assuming the wave vector k is in the z direction) can be written as a superposition of the left ($\hat{\varepsilon}_+$) and the right ($\hat{\varepsilon}_-$) circularly polarized components:

$$\vec{E}=\hat{\varepsilon}_x E\exp(-i\omega t)+\text{c.c.}$$
$$=\frac{1}{\sqrt{2}}(\hat{\varepsilon}_+ +\hat{\varepsilon}_-)E\exp(-i\omega t)+\text{c.c.}$$

CPT occurs in the transitions $F\leftrightarrow F'$ only when $F'\leqslant F$ and is manifested by Λ-type transition chains connecting the degenerate hyperfine ground sublevels (shown as solid lines in Fig. 1) [18,19]. Morris and Shore showed [16] that a unitary transformation can change the wave function basis into a new set of eigenstates of the interaction Hamiltonian, one of which is decoupled from the excitation field and corresponds to the dark states. For the $F=2\leftrightarrow F'=2$ transition, besides the well-known optical pumping that transfers the atoms to the noninteracting, hyperfine ground $F=1$ state, the atomic population can also be trapped in a coherent superposition of three hyperfine ground sublevels ($m=2$, 0, and -2) connected by the Λ-type transition chain to the sublevels of the excited state ($m=1$ and -1) [Fig. 1(b)]. For a resonant coupling field, the dark state can be written as (omitting an arbitrary phase factor)

$$|\phi\rangle=\tfrac{1}{2}\{\sqrt{\tfrac{3}{2}}|-2\rangle+|0\rangle+\sqrt{\tfrac{3}{2}}|2\rangle\}. \tag{1}$$

Here $|i\rangle$ ($i=0,\pm1,\pm2$) denotes the ground magnetic $m=i$ sublevel. For the $F=2\leftrightarrow F'=1$ transition, there exists two Λ-type chains: one connecting three sublevels ($m=2$, 0, and -2) of the hyperfine ground state to the sublevels ($m=1$ and -1) of the excited state, and the other connecting the two hyperfine ground sublevels ($m=1$ and -1) to the sublevel ($m=0$) of the excited state [Fig. 1(a)]. The corresponding dark states are [21]

$$|\phi_1\rangle=\sqrt{\tfrac{1}{8}}\{|-2\rangle-\sqrt{6}|0\rangle+|2\rangle\} \tag{2}$$

and

$$|\phi_2\rangle=\sqrt{\tfrac{1}{2}}\{|-1\rangle-|1\rangle\}, \tag{3}$$

respectively. General expressions of dark states generated by an arbitrary, ellipticaly polarized light field can be derived from the formalism presented in Refs. [19, 20]. Note that the dark states are a coherent mixture of the hyperfine ground sublevels. For a circularly polarized coupling field, no dark state can be generated and CPT does not exist. For example, for the $F=2\leftrightarrow F'=2$ transition, optical pumping by a left (right) circularly polarized light will trap the atoms in the $m=2$ ($m=-2$) sublevel while for the $F=2\leftrightarrow F'=1$ transition, the atoms will be trapped in the $m=2$ and 1 or $m=-2$ and -1 sublevels, respectively (also to the noninteracting ground $F=1$ sublevels). This may be referred to as incoherent population trapping because the optical pumping does not leave the trapped atoms in a coherent mixture of the ground sublevels. Since CPT depends on the polarization of the coupling field, it can be explored by a weak probe laser tuned to the *same* atomic transition as the coupling laser. The transition probability induced by a probe field E_p between the dark states Φ generated by a linearly polarized coupling field and the excited hyperfine state F' (including all magnetic sublevels) is given by [23]

$$P(\phi,F')=\sum_{i,m}|\langle\phi_i|\vec{D}\cdot\vec{E}_p|F',m'\rangle|^2. \tag{4}$$

When the probe laser is polarized parallel to the coupling field, the probe field can be written as

$$\vec{E}_p=\hat{\varepsilon}_x E_p\exp(-i\omega t)+\text{c.c.}$$
$$=\frac{1}{\sqrt{2}}(\hat{\varepsilon}_+ +\hat{\varepsilon}_-)E_p\exp(-i\omega t)+\text{c.c.} \tag{5}$$

When the probe laser is polarized perpendicular to the coupling laser, the probe field can be written as

$$\vec{E}_p = \hat{\varepsilon}_y E_p \exp(-i\omega t) + \text{c.c.}$$
$$= \frac{-i}{\sqrt{2}}(\hat{\varepsilon}_+ - \hat{\varepsilon}_-)\{E_p \exp(-i\omega t) + \text{c.c.}\}. \quad (6)$$

We define $P_\perp(\phi,F')$ and $P_\parallel(\phi,F')$ as the transition probabilities of the probe excitation for the y-polarized and the x-polarized probe field, respectively. It is easy to show that $P_\parallel(\phi,F')=0$ and $P_\perp(\phi,F')\neq 0$ for both the $F=2\leftrightarrow F'=1$ and $F=2\leftrightarrow F'=2$ transitions. The dark states generated by the coupling laser are decoupled from the x-polarized probe laser due to the destructive interference between the excitation paths and no excitation by the probe laser occurs. In contrast, the dark states are coupled to the y-polarized probe laser through the constructive interference and the atoms in the dark states will be excited. The interference contrast for the two polarization directions of the probe field on both the transition $F=2\leftrightarrow F'=1$ and the transition $F=2\leftrightarrow F'=2$ is given by

$$C = \frac{P_\perp(\phi,F') - P_\parallel(\phi,F')}{P_\perp(\phi,F') + P_\parallel(\phi,F')} = 100\%. \quad (7)$$

Because the two circularly polarized components in $\hat{\varepsilon}_+$ and $\hat{\varepsilon}_-$ have a π phase difference between the x-polarized probe field and the y-polarized probe field, the interference of the excitation paths between the dark states and the excited hyperfine state changes from destructive to constructive for the two polarization directions. Therefore, the polarization dependence of the probe excitation is a signature of CPT.

A weak probe laser tuned to a *different* set of the hyperfine transitions from the coupling laser will excite the atoms from the dark states to the excited state. Since the dark states are a coherent superposition of the ground magnetic sublevels, the interference between the multiple interaction paths will also cause a variation of the transition probability as the probe field polarization changes. Because the dipole moments differ among different hyperfine transitions, the constructive and destructive interferences generally do not have 100% contrast when the coupling field and the probe field are tuned to different transitions. For the ^{87}Rb D_1 transitions, when a linearly polarized, resonant coupling field produces the dark state $|\phi\rangle$ on the $F=2\leftrightarrow F'=2$ transition and a probe field drives the $F=2\leftrightarrow F'=1$ transition, we found that constructive interference occurs in the probe excitation for the probe field polarized parallel to the coupling field and destructive interference occurs for the probe field polarized perpendicular to the coupling field. The interference contrast is given by

$$C = \frac{P_\perp(\phi,F') - P_\parallel(\phi,F')}{P_\perp(\phi,F') + P_\parallel(\phi,F')} = -61\%. \quad (8)$$

Similarly, when a linearly polarized, resonant coupling field produces the dark state $|\phi_1\rangle$ and $|\phi_2\rangle$ on the $F=2\leftrightarrow F'=1$ transition and a linearly polarized probe field drives the transition $F=2\leftrightarrow F'=2$, the probe field polarized parallel to the coupling field leads to the constructive interference and the probe field polarized perpendicular to the coupling field leads to the destructive interference. The interference contrast is

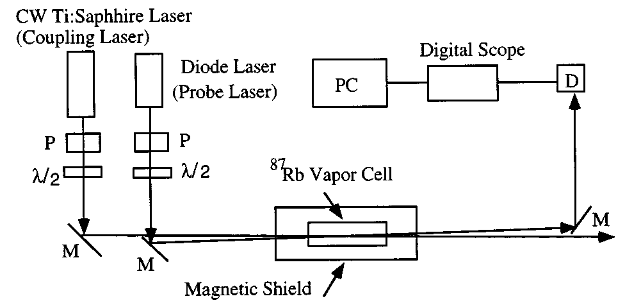

FIG. 2. Experimental arrangement for observation of CPT in Doppler-broadened, multilevel degenerate, open ^{87}Rb systems. *P*'s, polarizers; λ/2's, half-wave plates; *M*'s, mirrors; *D*, photodiode detector; PC, personal computer.

$$C = \frac{P_\perp(\phi,F') - P_\parallel(\phi,F')}{P_\perp(\phi,F') + P_\parallel(\phi,F')} = -58\%. \quad (9)$$

Note that for an open multilevel system in the steady state, the atomic population in the bright dressed states is completely depleted by the optical pumping. The polarization dependence of the probe excitation is observable only when there are atoms trapped in the dark states. As discussed before, a circularly polarized coupling field produces no dark state and the optical pumping only leads to incoherent population trapping in the ''edge'' magnetic sublevels. Since these states are not coherent superposition of the magnetic sublevels of the ground hyperfine state, there will be no polarization dependence of the probe excitation. Therefore, the polarization dependence of the atomic excitation by a weak probe laser coupled to the same or different transition as that of the coupling laser is caused by the interference of the excitation paths between the dark states and the excited state, which is an indicative feature of CPT in open multilevel atomic systems.

III. EXPERIMENTAL RESULTS

The experimental arrangement is shown schematically in Fig. 2. The experiment was performed in a room-temperature, ^{87}Rb isotope (the isotope abundance was 95%) vapor cell without any buffer gas. The estimated Rb density was $\sim 2\times 10^{10}\,\text{cm}^{-3}$ [24]. The vapor cell was 7.5 cm long and was magnetically shielded by a 15-cm-long, μ-metal tube. The measured residual magnetic field was $\leqslant 0.03$ G. The hyperfine splitting of the excited $5P_{1/2}$, $F'=2$, and $F'=1$ states is 816 MHz, which is greater than the Doppler width of ~ 540 MHz. Therefore, the Doppler-broadened absorption lines for the two transitions are well resolved. The coupling field was provided by a Ti:sapphire laser (Coherent 899-21) with a beam diameter ~ 2 mm and power ~ 80 mW. An extended-cavity diode laser was used as the weak probe laser. The beam diameter of the diode laser was ~ 1 mm and the power was $\sim 0.2\,\mu$W. The beams of the Ti:sapphire laser and the diode laser were overlapped in the Rb vapor cell with an angle $\sim 0.5°$. The linewidth of the Ti:sapphire laser was $\leqslant 5$ MHz while the diode laser linewidth was ~ 1 MHz. After passing through the Rb cell, the probe beam was detected by a photodiode. The photodiode signal was sent to a digital oscilloscope and the digitized data were stored in a PC. During the experiment, the Ti:sapphire laser was tuned to the center of the D_1 $F=2\leftrightarrow F'=1$ or 2 transition at ~795 nm while the diode laser frequency was scanned across the D_1 $F=2\leftrightarrow F'=1$ and 2 transitions.

Figure 3(a) shows the absorption spectrum of the weak probe laser scanned across the ^{87}Rb D_1 $F=2\leftrightarrow F'=1$ and $F'=2$ transitions when the coupling laser is absent. When the linearly polarized coupling laser was turned on and tuned to the center of the $F=2\leftrightarrow F'=1$ transition, the probe absorption spectrum is shown [Figs. 3(b) and 3(c)]. When the probe laser polarization was parallel to that of the coupling laser [Fig. 3(b)], the absorption at the $F=2\leftrightarrow F'=1$ transition is suppressed by the destructive interference, indicating CPT in the dark states. The broad minimum at the $F=2\leftrightarrow F'=1$ transition reflects the thermal distribution of the trapped Rb atoms and shows that CPT is effective for most of the Rb atoms in the thermal velocity distribution. This is expected from the Doppler-free Λ-type coupling of the two circular components of the linearly polarized laser. The weak probe laser simply maps out the trapped Rb atoms in the dark states and plays no role in the creation of the dark states. This is different from the CPT (or EIT) observed in the nondegenerate three-level Λ-type system coupled by two lasers with different frequencies [2,3,8–10]. As the coupling laser intensity decreases, the absorption near the line center increases and the broad minimum becomes narrower. At higher coupling laser intensities, the off-resonant excitation of the Rb atoms to the $F'=2$ state becomes appreciable. This leads to the transfer of some Rb atoms to the ground $F=1$ hyperfine state and results in fewer Rb atoms trapped in the ground $F=2$ dark states. As discussed before, the same probe laser induces the constructive interference on the $F=2\leftrightarrow F'=2$ transition (at the detuning 816 MHz) at which the absorption is therefore enhanced. When the probe laser was polarized perpendicular to the coupling laser [Fig. 3(c)], the constructive interference occurs for the transition $F=2\leftrightarrow F'=1$ and the absorption is enhanced. At the same time, the destructive interference occurs for the transition $F=2\leftrightarrow F'=2$ at which the absorption is suppressed. It is important to note that the maximum absorption under the constructive interference is ~50%, indicating that a large number of atoms are trapped in the dark states despite the competing optical pumping that transfers the atoms to the noninteracting, ground $F=1$ hyperfine state. This is consistent with the theoretical study of Ref. [21] based on the homogeneous Rb system. Quantitative comparison with the theory requires a detailed analysis including the Doppler effect and the off-resonant coupling with the $F=2\leftrightarrow F'=2$ transition, which is quite complicated and will be left for future consideration. The interference contrast of the probe excitation for the two-probe polarization directions, ($\perp$ probe absorption $-\parallel$ probe absorption)/($\perp$ probe absorption $+\parallel$ probe absorption), is plotted in Fig. 3(d). It shows that near the line center, the interference contrast for the two orthogonal polarization directions is close to 100% when the probe laser is coupled to the same transition $F=2\leftrightarrow F'=1$ as that of the coupling laser. The interference contrast is ~-45% when the probe laser is coupled to the different transition $F=2\leftrightarrow F'=2$ from that of the coupling laser. These measurements agree well with the previous analysis.

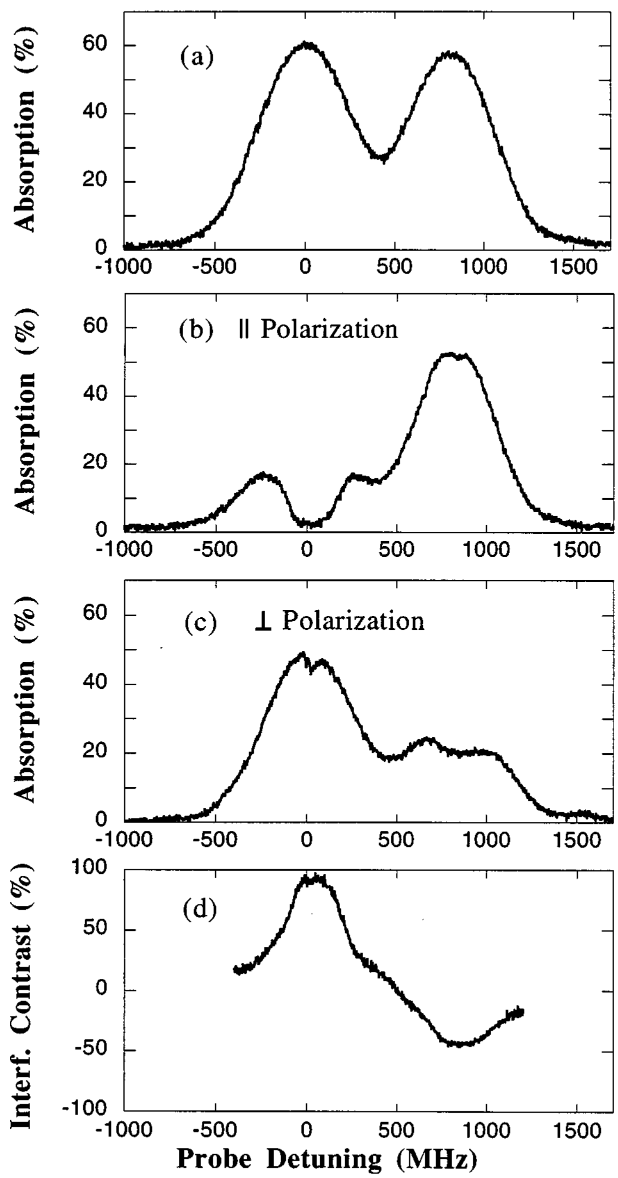

FIG. 3. Measured probe absorption spectra versus the probe laser detuning from the D_1 $F=2\leftrightarrow F'=1$ transition. (a) The probe absorption spectrum without the presence of the coupling laser. The peak at the zero detuning corresponds to the ^{87}Rb D_1 $F=2\leftrightarrow F'=1$ transition while the peak at the detuning 816 MHz corresponds to the $F=2\leftrightarrow F'=2$ transition. (b) and (c) show the probe absorption spectra when a linearly polarized coupling laser is tuned to the center of the $F=2\leftrightarrow F'=1$ transition. (b) The probe laser was linearly polarized parallel to the coupling laser. (c) The probe laser was linearly polarized perpendicular to the coupling laser. (d) The interference contrast ($\perp$ probe absorption $-\parallel$ probe absorption)/($\perp$ probe absorption $+\parallel$ probe absorption) for the two orthogonal polarization directions of the probe laser. Note the phase reversal of the interference when the probe laser was tuned from the $F=2\leftrightarrow F'=1$ transition to the $F=2\leftrightarrow F'=2$ transition.

For comparison, we also recorded the probe absorption spectrum when the coupling laser was circularly polarized and tuned to the same $F=2\leftrightarrow F'=1$ transition. For a left (right) circularly polarized coupling laser, the atoms will be optically pumped into the ground $m=1$ and 2 ($m=-1$ and

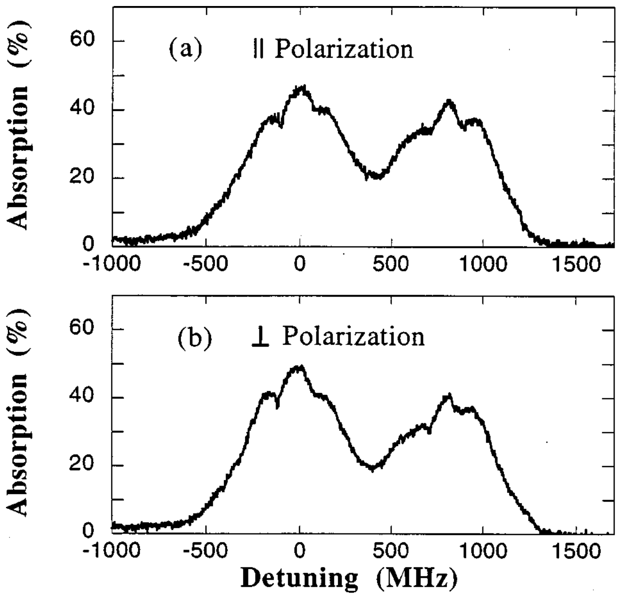

FIG. 4. Measured probe absorption spectra versus the probe laser detuning from the $F=2\leftrightarrow F'=1$ transition with a circularly polarized coupling laser tuned to the center of the $F=2\leftrightarrow F'=1$ transition. (a) The probe laser was linearly polarized in the x direction. (b) The probe laser was linearly polarized in the y direction.

-2) sublevels (also to the noninteracting ground $F=1$ hyperfine state), and no CPT exists. Since the trapped atoms are not in a coherent superposition of the ground magnetic sublevels, the probe absorption spectrum should be independent of the probe polarization. This is indeed the case as shown by the probe absorption spectra presented in Fig. 4(a) [4(b)] for the probe field polarized parallel (perpendicular) to the coupling field.

In Fig. 5, we present the CPT measurement for the ^{87}Rb D_1 $F=2\leftrightarrow F'=2$ transition. The dark state was generated by the coupling laser tuned to the center of the $F=2\leftrightarrow F'=2$ transition. Figure 5(b) shows the probe absorption spectrum for the probe laser polarized parallel to the coupling laser. The absorption at the $F=2\leftrightarrow F'=2$ transition was suppressed by the destructive interference, while at the $F=2\leftrightarrow F'=1$ transition (at the detuning -816 MHz) the absorption is enhanced by the constructive interference. When the probe laser is polarized perpendicular to the coupling laser, the phase is reversed; the destructive interference occurs at the $F=2\leftrightarrow F'=1$ transition while the constructive interference occurs at the $F=2\leftrightarrow F'=2$ transition [Fig. 5(c)]. Figure 5(d) shows the interference contrast of the probe excitation for the two polarization directions. Again, when the probe laser and the coupling laser drive the same transition ($F=2\leftrightarrow F'=2$), the contrast is close to 100%; when the two lasers drive the different transitions, the contrast is ~45% with a phase reversal. These observations again agree well with the previous analysis. Note that the number of atoms trapped in the dark state of the $F=2\leftrightarrow F'=2$ transition is smaller than that of the $F=2\leftrightarrow F'=1$ transition, indicating that more atoms are transferred by the optical pumping to the noninteracting $F=1$ ground state. This may be due to the fact that there is only one dark state for the $F=2\leftrightarrow F'=2$ transition while there are two dark states for the $F=2\leftrightarrow F'=1$ transition.

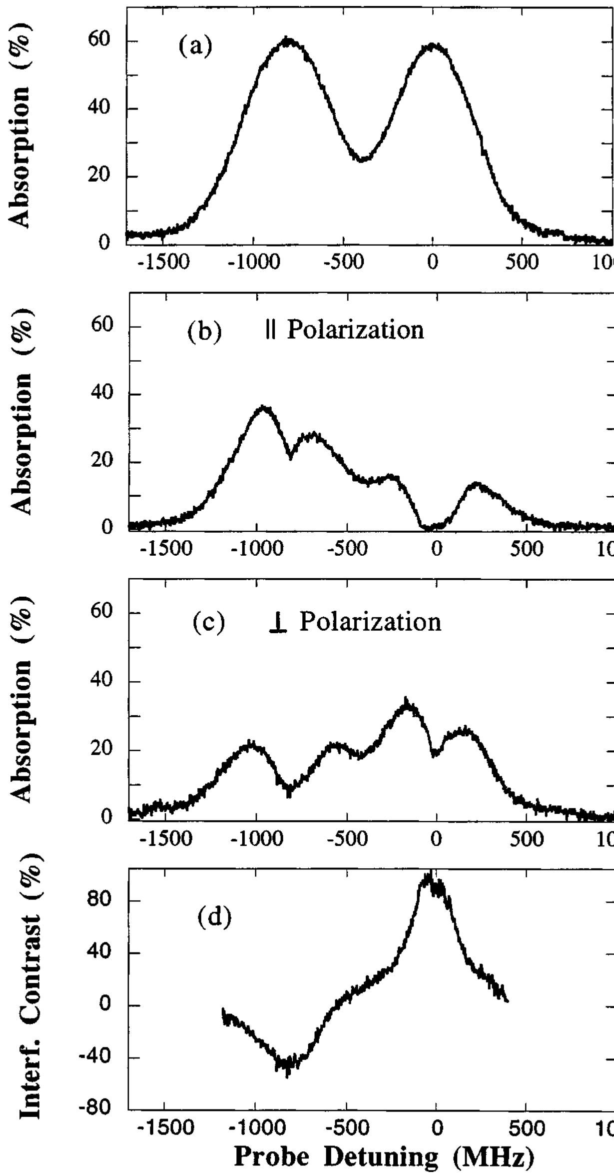

FIG. 5. Measured probe absorption spectra versus the probe laser detuning from the $F=2\leftrightarrow F'=2$ transition. (a) The probe absorption spectrum without the presence of the coupling laser. The peak at the zero detuning corresponds to the ^{87}Rb D_1 $F=2\leftrightarrow F'=2$ transition while the peak at the detuning -816 MHz corresponds to the $F=2\leftrightarrow F'=1$ transition. (b) and (c) show the probe absorption spectra when a linearly polarized coupling laser is tuned to the center of the $F=2\leftrightarrow F'=2$ transition. (b) The probe laser was linearly polarized parallel to the coupling laser. (c) The probe laser was linearly polarized perpendicular to the coupling laser. (d) The interference contrast (the $\perp$ probe absorption $-$ the $\parallel$ probe absorption)/(the $\perp$ probe absorption $+$ the $\parallel$ probe absorption) for the two orthogonal polarization directions of the probe laser.

For comparison, we present the measured probe absorption spectra in Fig. 6 for the circularly polarized coupling laser tuned to the same $F=2\leftrightarrow F'=2$ transition. The left (right) circularly polarized coupling laser does not create any dark state and the optical pumping traps some atoms in the ground hyperfine $m=2$ ($m=-2$) sublevel. The probe absorption does not depend on its polarization as verified by the measured probe spectrum shown in Figs. 6(a) and 6(b)

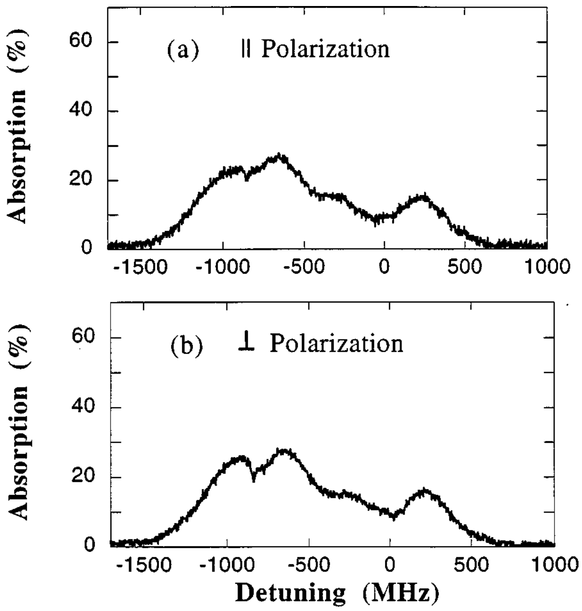

FIG. 6. Measured probe absorption spectra versus the probe laser detuning from the $F=2 \leftrightarrow F'=2$ transition with a circularly polarized coupling laser tuned to the center of the $F=2 \leftrightarrow F'=2$ transition. (a) The probe laser was linearly polarized in the x direction. (b) The probe laser was linearly polarized in the y direction.

for the two orthogonal polarization directions of the probe laser.

We also recorded the polarization dependence of the probe absorption spectrum across the ^{87}Rb $F=1 \leftrightarrow F'$ transitions when the linearly polarized coupling laser was tuned to the center of the $F=1 \leftrightarrow F'=2$ transition. No CPT can be achieved for the transition of $F'>F$, and the optical pumping will deplete atomic population from the ground $F=1$ hyperfine state to the ground $F=2$ hyperfine state. This agrees with the experimental measurements shown in Fig. 7(b) (the probe field is polarized parallel to the coupling field) and Fig. 7(c) (the probe field is polarized perpendicular to the coupling field). For reference, the probe absorption spectrum without the coupling laser is shown in Fig. 7(a). As expected, there is no dependence of the probe absorption on the probe polarization.

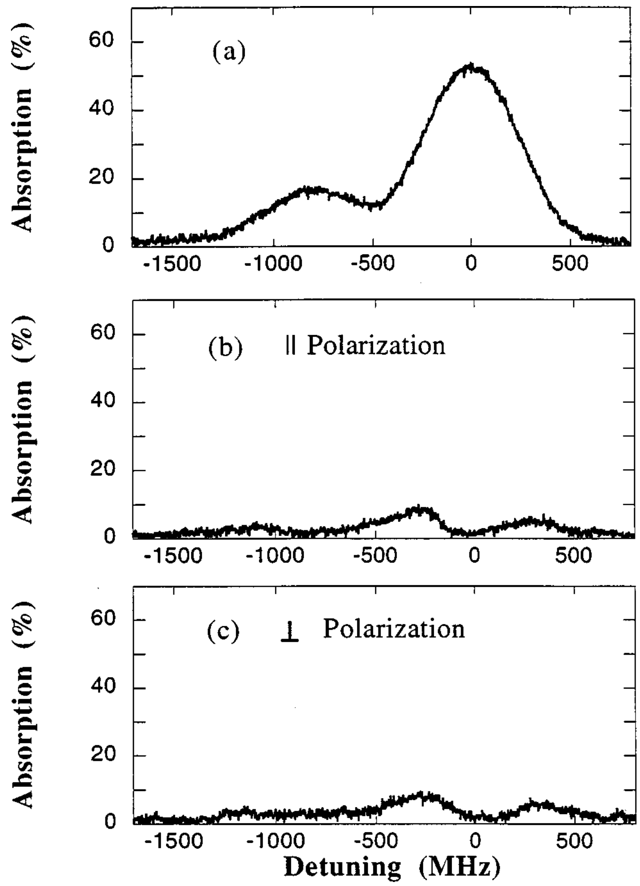

FIG. 7. Measured probe absorption spectra versus the probe laser detuning from the $F=1 \leftrightarrow F'=2$ transition. (a) The probe absorption spectrum when the coupling laser was blocked. (b) and (c) show the probe spectrum with a linearly polarized coupling laser tuned to the center of the $F=1 \leftrightarrow F'=2$ transition. (b) The probe laser was linearly polarized parallel to the coupling laser. (c) The probe laser was linearly polarized perpendicular to the coupling laser.

IV. CONCLUSION

In conclusion, we have reported a direct observation of CPT in an inhomogeneously broadened, open multilevel atomic system. With a linearly polarized coupling laser, the Doppler shift is completely compensated for the two circular components of the coupling field that connect the Λ-type coupling chains and establish the dark states. Although optical pumping depletes the atomic population by transferring atoms to the noninteracting ground hyperfine state, a large number of the atoms survive the optical pumping and are trapped in the dark state(s) which decouple(s) from the radiation field that generates it. CPT was demonstrated by the observation of polarization dependence of the absorption for a weak probe laser that is tuned to the same or different transition as that of the coupling laser. The polarization dependence of the probe absorption is manifested by the quantum interference of the excitation paths between the dark states and the excited state. For the ^{87}Rb D_1 transitions, the interference contrast of ~100% near the line center was observed for the two orthogonal polarization directions of the probe laser tuned to the same transition as that of the coupling laser. When the probe laser was tuned to a different transition from that of the coupling laser, the interference changes the sign and the observed interference contrast was reduced to ~45%. Our experiment shows that effects of CPT can be important in diverse physical phenomena in which a multilevel atomic system (either open or close) interacting with a moderate coupling laser, such as cooling and trapping of atoms, a laser without population inversion, and optical pumping of atoms and molecules. CPT in multilevel atomic systems may be useful in a number of applications such as polarization control of multiple laser excitation and ionization of atoms and molecules, enhancement of nonlinear optical susceptibilities, and manipulation of neutral atoms in traps and optical lattices.

ACKNOWLEDGMENTS

This work was supported by the NSF and the U.S. Army Research Office (Grant No. DAAH04-95-1-0534).

[1] E. Arimondo, in *Progress in Optics*, edited by E. Wolf (Elsevier Science, Amsterdam, 1996), Vol. XXXV, p. 257.
[2] E. Arimondo and G. Orriols, Nuovo Cimento Lett. **17**, 333 (1976).
[3] H. R. Gray, R. M. Whitley, and C. R. Stroud, Opt. Lett. **3**, 218 (1989).
[4] A. Aspect *et al.*, Phys. Rev. Lett. **61**, 826 (1988).
[5] F. Papoff, F. Mauri, and E. Arimondo, J. Opt. Soc. Am. B **9**, 321 (1992).
[6] A. Hemmerich *et al.*, Phys. Rev. Lett. **75**, 37 (1995).
[7] T. Esslinger *et al.*, Phys. Rev. Lett. **76**, 2432 (1996).
[8] J. E. Field, K. H. Hahn, and S. E. Harris, Phys. Rev. Lett. **67**, 3062 (1991); S. E. Harris, Phys. Today **50** (7), 36 (1997).
[9] M. Xiao, Y. Li, S. Jin, and J. Gea-Banacloche, Phys. Rev. Lett. **74**, 666 (1995).
[10] R. R. Moseley, S. Shepherd, D. J. Fulton, B. D. Sinclair, and M. H. Dun, Phys. Rev. Lett. **74**, 670 (1995).
[11] S. E. Harris, Phys. Rev. Lett. **62**, 1033 (1989).
[12] O. Kocharovskaya, Phys. Rep. **219**, 175 (1992).
[13] M. O. Scully, Phys. Rep. **219**, 191 (1992).
[14] K. Hakuta, L. Marmet, and B. P. Soicheff, Phys. Rev. Lett. **66**, 596 (1991); G. Z. Zhang, K. Hakuta, and B. P. Stoicheff, *ibid.* **71**, 3099 (1993).
[15] M. O. Scully, Phys. Rev. Lett. **67**, 1154 (1991); A. S. Zibrov, H. G. Robinson, V. L. Velichansky, L. W. Hollberg, and M. O. Scully, *ibid.* **79**, 2959 (1997).
[16] M. Jain, M. Xia, G. Y. Yin, A. J. Merriam, and S. E. Harris, Phys. Rev. Lett. **77**, 4326 (1996).
[17] J. R. Morris and B. W. Shore, Phys. Rev. A **27**, 906 (1983).
[18] F. T. Hioe and C. E. Carroll, Phys. Rev. A **37**, 3000 (1988).
[19] V. S. Smirnov, A. M. Tumaikin, and V. I. Yudin, Zh. Eksp. Teor. Fiz. **96**, 1613 (1989) [Sov. Phys. JETP **69**, 913 (1989)].
[20] V. Milner, B. M. Chernobrod, and Y. Prior, Europhys. Lett. **34**, 557 (1996).
[21] H. Y. Ling, Y. Li, and M. Xiao, Phys. Rev. A **53**, 1014 (1996).
[22] V. Milner and Y. Prior, Phys. Rev. Lett. **80**, 940 (1998).
[23] A. R. Edmonds, *Angular Momentum in Quantum Mechanics* (Princeton University Press, Princeton, NJ, 1974), p. 76.
[24] A. M. van der Spek, J. J. L. Mulders, and L. W. G. Steenhuysen, J. Opt. Soc. Am. B **5**, 1478 (1988).