Suppression and recovery of the trapping of atoms using a ladder-type electromagnetically induced transparency

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Subnatural linewidth in an optical transition in Cs was obtained by the suppression and recovery of the trapping of atoms. Cold Cs atoms in a magneto-optical trap (MOT) were irradiated using a weak probe laser to suppress MOT loading. When a counterpropagating coupling laser was directed to be resonant with the upper transition, the probe laser was induced to transmit and the MOT loading was recovered. This work investigates quantitatively this behavior by applying simulated electromagnetically induced transparency, taking into account the linewidth of the lasers as a decoherence source.

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Electromagnetically induced transparency (EIT) has attracted considerable attention over the last few decades [1]. The dramatic change in the susceptibility of the EIT system supports a means of manipulating the properties of the photons and the medium. Conventionally, this concept has been extensively applied to laser-controlled quantum dynamics in atomic or molecular systems, and to the robust and complete population transfer between quantum levels [2]. In the newly developed field of quantum information, applications of the EIT system have supported various experiments, such as photon switching [3,4] or atom-photon entanglement [5,6]. Other applications, such as lasing without inversion [7], laser cooling below one-photon recoil energy [8], ultrasensitive magnetometers [9], and atomic clocks [10] have also seen marked progress. Additionally, the ability of the atom-photon interaction to generate nonlinear effects, via the EIT process, has opened up the possibility of generating electro-optical devices and nonlinear optics using electromagnetically induced gratings [11] or electromagnetically induced focusing [12]. Atomic states can also be probed by exploiting quantum interference by controlling the coupling field [13,14]. Λ- and V-type EITs have been utilized and numerous related investigations have also been performed using a three-level ladder-type system in inhomogeneous broadening media [12,14–19]. This work presents a three-level ladder-type EIT configuration in the low-lying atomic Rydberg state that is obtained by the suppression and recovery of the trapping of atoms by controlling the effect of the probe field on laser-cooled atoms. A background-free spectrum was obtained and a subnatural linewidth feature observed because of quantum interference. This behavior was quantitatively examined by applying the simulated line shape of the electromagnetically induced transparency to our experimental data to solve the steady-state optical Bloch equations by approximating the induced transparency to our experimental data to solve the transition $|6^2 S_{1/2}, F=4\rangle \rightarrow |6^2 P_{3/2}, F=5\rangle$, and the frequency of an intense coupling beam is scanned across the transition $|6^2 P_{3/2}, F=5\rangle \rightarrow |8^2 S_{1/2}, F=4\rangle$. The Rabi frequency of the probe and the coupling transitions are labeled $\Omega_p$ and $\Omega_c$, respectively. $\Gamma_1$ and $\Gamma_2$ describe the decay rates of the intermediate and upper states. The ladder-type EIT configuration was applied in a typical Cs cell MOT. The temperature of the MOT was determined to be about 100 µK by the time of flight method. The density was estimated to be $10^9$ cm$^{-3}$. Figure 2 displays the experimental setup. An external cavity diode laser (Sacher TEC-100, 100 mW) was operated at the MOT trapping frequency, and was red-detuned by 10 MHz from $|6^2 S_{1/2}, F=4\rangle \rightarrow |6^2 P_{3/2}, F=5\rangle$ transition. Another DBR diode laser (SDL-5712-H1, 50 mW) was frequency stabilized at the transition $|6^2 S_{1/2}, F=3\rangle \rightarrow |6^2 P_{3/2}, F=3\rangle$, forcing the population of the $|6^2 S_{1/2}, F=3\rangle$ to retrace the MOT transition cycling. The probe beam derived from the trapping laser was frequency shifted using an acoustic-optical modulator (AOM) to the resonance at $|6^2 S_{1/2}, F=4\rangle \rightarrow |6^2 P_{3/2}, F=5\rangle$ transition. A coupling laser (Coherent 899–29 autoscan Ti:sapphire ring laser) was scanned across the $|6^2 P_{3/2}, F=5\rangle \rightarrow |8^2 S_{1/2}, F=4\rangle$ transition. The probe and the coupling

FIG. 1. The relevant energy level diagrams of Cs atoms involved in the experiment. $\Omega_p$, $\Omega_c$: Rabi frequency of the probe and coupling lasers; $\Delta_p$, $\Delta_c$: detuning of the probe and coupling lasers; $\Gamma_2$, $\Gamma_3$: decay rates of the intermediate and upper states.

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beams were linearly polarized in parallel and counterpropagated through the cold cloud of Cs MOT. The linewidths of both lasers were typically less than 1 MHz. The fluorescence from the Cs MOT was collimated using a lens and detected by a photodiode (Electro-Optics Technology ET4000); the data were sent to a computer via an interface card (National Instruments, 6052E) and analyzed using the LABVIEW program. In most of the EIT configurations, the probe laser frequency was scanned at fixed coupling frequency. In this experiment, the probe laser was on resonance ($\Delta_p=0$) and frequency stabilized while the coupling laser was scanned. Absorption of the probe field by the atoms in the MOT yielded an apparent transmission peak as the coupling field was scanned around resonance [14]. This transmission peak is produced by the quantum interference between the transition pathways that is induced by the probe and the coupling fields, and enabled the hyperfine structure of the Rydberg states of the atomic medium below the natural linewidth range to be accessed.

The experiment was performed in a time sequence defined by the LABVIEW program, as shown in Fig. 3, to obtain a background-free signal and to prevent power broadening from the MOT fields. Initially, the cold atoms (MOT) were loaded from a room temperature vapor cell for 1000 ms. In this loading stage, the trapping laser, the repumping laser and the quadrupole magnetic field (anti-Helmholtz coils) were turned on to load the atoms. In the following stage, both the probe beam and the coupling beam were engaged into the interaction process for 500 ms. The weak probe beam was kept on during this period, which knocked out the cold atoms. Therefore, the loading of the Cs MOT was greatly suppressed by the probe beam. During the interaction period, the trapping beam pulse and the coupling beam pulse were set to run alternatively at 70 kHz, to prevent the strongly dressed states effect among the MOT transitions. In the next stage, all of the fields were turned off for a time window of 1 ms following the period of interaction to prevent the perturbation of residual fields on the following detection stage (not present in Fig. 3). The trapping and the repumping beams were turned on for 50 ms to perform the laser-induced fluorescence and thus measure the number of atoms that remain in the MOT after the release stage. The MOT fluorescence was detected by a photodiode and the signal was time averaged. Finally, a trigger signal was applied to the control unit of the Ti:sapphire laser (coupling laser) to increase the frequency by a default value of 1 MHz.

Figure 4 presents a typical spectrum obtained by probing a low-lying excited Rydberg state in a two-step excitation scheme that involves the transitions $|6^2S_{1/2}, F=4\rangle \rightarrow |6^2P_{3/2}, F=5\rangle \rightarrow |8^2S_{1/2}, F=4\rangle$ for various coupling la-

![FIG. 2. The schematic diagram of the experimental setup. The frequency of an unrefracted Ti:Sa laser was calibrated via the room temperature EIT. AOM: acoustic-optical modulator; PD: photodiode; BS: beam splitter; M: mirror; AH coils: Anti-Helmholtz coils.](image)

![FIG. 3. The time sequence of the experiment. Atoms were loaded into the MOT for 1000 ms and allowed to interact with the probe and coupling (Ti:Sa laser) lasers for 500 ms. During the interaction time interval, the coupling and MOT lasers were triggered alternately at 70 kHz.](image)

![FIG. 4. The highly saturated spectrum from the suppression and recovery processes. The intensity of the probe beam is 80 $\mu$W/cm$^2$ and that of the coupling beam is 950 mW/cm$^2$.](image)
ser frequency. The broad spectrum and the nearly dc signal exhibited MOT fluorescence in the presence and absence of the probe beam during the interaction process. With the participation of the probe beam, the Cs MOT loading was strongly suppressed when the frequency of the coupling beam was far from resonance. Such suppression involves an almost background-free observation. The squarelike signal was associated with the power broadening of the coupling laser as it scanned across the resonance of the transition $|6^2P_{3/2}, F=5\rangle \rightarrow |8^2S_{1/2}, F=4\rangle$. The EIT was produced by the interference between the transition pathways of $|6^2S_{1/2}, F=4\rangle \rightarrow |6^2P_{3/2}, F=5\rangle$ and $|6^2P_{3/2}, F=5\rangle \rightarrow |8^2S_{1/2}, F=4\rangle$. This destructive interference prevented the absorption of the probe beam, causing the loading mechanism to be recovered. Hence, the number of atoms increased gradually as the coupling beam frequency approached resonance ($\Delta_g=0$). The recovery of the number of atoms because of the EIT process, reached its saturation value, reflecting the initial loading condition in the absence of the probe beam. The formation of the Cs MOT was depressed again when the coupling laser frequency was blue-detuned further from the resonance. The inset in Fig. 5 plots the power dependence of the suppression and the recovery signals at low probe beam intensity (about 80 $\mu$W/cm$^2$). The saturation linewidth of the recovery signals clearly decreased as the coupling beam intensity decreased, and the recovery signals exhibited a Lorentzian profile in the low-intensity regime. Both the amplitude and the linewidth of the recovery peaks declined as the coupling intensities declined. Such a behavior was quantitatively investigated by theoretically predicting the EIT line shape, including the linewidth of the lasers as a decoherence source in the simulation. Most works that have solved the steady state optical Bloch equations by using an approximation to the weak probe limit have suggested the following explicit formula for the off-diagonal term $\rho_{21}$, which reveals that the probe transition is as follows [18]:

$$\rho_{21} = \frac{-i\mu_{21}E_p}{(\Gamma_y/2 - i\Delta_p + (\Omega_y/2)^2[\Gamma_y/2 - i(\Delta_p + \Delta_c)]}$$

(1)

where $\mu_{21}$ is the transition dipole moment that involves the ground state and the intermediate state; $E_p$ is the probe field amplitude, and $\Omega_y$ is the Rabi frequency of the coupling field. $\Delta_p$ and $\Delta_c$ are the detuning of the probe and the coupling laser fields in terms of their respective atomic transition energies. The imaginary part of this equation stands for the probe absorption. Notably, no laser linewidth considerations were made. The elimination of the phase-jitters is reasonable only in the phase-coherent locking scheme [20]. However, the effect of the laser linewidth should be taken into account in general situations. Accordingly, the interaction Hamiltonian, including linewidth of the lasers as a decoherence source, was modified to determine the probe absorption profile numerically. The transmission linewidth [Eq. (1)] was calculated as a function of $\Omega_y$ with $\Omega_y=0.1$ MHz, $\Gamma_y=5.22$ MHz [21], and $\Gamma_3=2.18$ MHz [22]. Figure 6 plots the linewidth as a function of $\Omega_y$. The dashed line represents the theoretical result without including the laser linewidth, and the solid line represents a modified simulation including the linewidth of both fields at 400 kHz. The experimental data points (stars with error bars) are from the Lorentzian fit with linewidth as the only fitted parameter in the insets in Figs. 5(a)–5(d). Clearly, the experimental results matched the modified theory closely, indicating that the laser linewidth acts as a decoherence source in the present configuration. For clarity, the absorption profile obtained by the modified theory (using parameters of $\Omega_y=0.10$ MHz, $\Omega_y=2.07$ MHz, $\Gamma_2=5.22$ MHz, $\Gamma_3=2.18$ MHz, and the laser linewidths of 400
kHz) was plotted for comparison with the experimental data in Fig. 5, yielding the full width at half maximum (FWHM) of 3.44 MHz. This subnatural linewidth revealed that the suppression and recovery proceeded by the coherent EIT mechanism.

In conclusion, this investigation reported a novel method for measuring the Cs Rydberg states in the mechanism of EIT configuration by detecting the probe field absorption. This EIT process was conducted under the suppression and recovery proceeded by the coherent EIT of 3.44 MHz. This subnatural linewidth revealed that the suppression and recovery of the trapping of the cold Cs atoms. The residual Doppler width can be neglected when the laser-cooled atomic sample is used. The experiment also demonstrated the coherent properties between the transition processes and provided an almost background-free platform elucidating the high-lying states. People can use this method of suppression and recovery of the trapping of atoms in all types (A-, V-, and ladder-type) of EIT to investigate the properties of quantum interference.

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