Line narrowing of electromagnetically induced transparency in Rb with a longitudinal magnetic field

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Electromagnetically induced transparency (EIT) experiments in Λ-type systems benefit from the use of hot vapor where the thermal averaging results in reducing the width of the EIT resonance well below the natural linewidth. Here, we demonstrate a technique for further reducing the EIT width in room-temperature vapor by the application of a small longitudinal magnetic field. The Zeeman shift of the energy levels results in the formation of several shifted subsystems; the net effect is to create multiple EIT dips each of which is significantly narrower than the original resonance. We observe a reduction by a factor of 3 in the D_2 line of ^{87}Rb with a field of 3.2 G.

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The phenomenon of electromagnetically induced transparency (EIT) [1,2], in which a strong control laser is used to modify the properties of a medium for a weak probe laser, has recently found applications in slowing of light [3] (for use in quantum-information processing) and white-light cavities [4] (for use in gravitational wave detection). In these applications, it is the anomalous dispersion near the EIT resonance that is responsible for the effects. Thus, the narrower the EIT resonance, the more pronounced these effects. Narrow EIT resonances also play an important role in high-resolution spectroscopy [5–7] and tight locking of lasers to optical transitions. We have recently shown [8] that the use of room-temperature vapor for EIT experiments is actually advantageous because the EIT resonance gets narrowed due to thermal averaging. In other words, the thermal motion of the atoms, and the consequent "Doppler broadening," has the counterintuitive effect of reducing the width of the transparency window. The EIT linewidth is therefore much smaller than the natural linewidth (Γ), even when the control laser is strong enough to cause a large ac Stark shift of the levels (creation of widely separated dressed states [9] and an Autler-Townes doublet).

In this work, we demonstrate a technique for further reducing the linewidth in room-temperature vapor, namely, by the application of a longitudinal magnetic field. The energies of the magnetic sublevels get shifted by different amounts, and several three-level subsystems are formed. The effect of the shifted subsystems is to create multiple EIT resonances—a central dip with sidebands—each of which is significantly narrower than the original resonance. We observe a reduction by a factor of 3, from 0.75Γ to 0.25Γ, in a Λ system in the D_2 line of ^{87}Rb with a field of 3.2 G. There has been a recent report [10] of the splitting (and narrowing by a factor of $\sqrt{2}$) of EIT resonances with the application of a magnetic field. But the starting EIT width was very large ($>5\Gamma$), and consequently a large field of 43 G was required to split the EIT channels.

We must also contrast our work with studies using the closely related phenomenon of coherent population trapping (CPT) in Λ systems [11,12]. CPT experiments use phase-coherent lasers to create a dark nonabsorbing state of the atoms, whereas EIT experiments use independent lasers and create transparency at the line center because of the ac Stark shift of the excited state caused by the control laser (dressed states) and quantum interference between the decay channels from the dressed states [13]. The width of the CPT resonance can be extremely small compared to the linewidth of the excited state because it is limited only by the decoherence rate between the two ground levels. In addition to using phase-coherent control and probe beams, CPT experiments require (i) roughly equal powers in the two beams, (ii) detuning of the two beams (equally) from resonance to decrease the decohering effect of the excited state, and (iii) the use of a buffer gas or antirelaxation coating in the vapor cell to increase the coherence time. The scan axis is not the laser frequency but the difference frequency between the two lasers (i.e., the two ground levels), which is of the order of 1–10 GHz in alkali-metal atoms. Linewidths of around 50 Hz for a ground interval of 9.1 GHz have been observed in room-temperature Cs vapor [14], representing an observed Q of 2×10^8—similar to a 1.5-MHz linewidth of an optical transition. Furthermore, the 50-Hz linewidth is not really subnatural because the natural linewidth of the upper ground level is <1 Hz. It is interesting to note that, even for CPT-type experiments with excited metastable states in He, the use of hot vapor has been recently shown to be beneficial in narrowing the resonance [15]. Small magnetic fields have also been used in CPT experiments to lift the degeneracy of the dark resonances [16], but there is no significant narrowing.

The relevant energy levels forming the Λ system in the D_2 line of ^{87}Rb are shown in Fig. 1(a). The strong control laser drives the $|1\rangle\leftrightarrow|2\rangle$ transition with Rabi frequency Ω_c and detuning Δ_c, while the weak probe measures absorption on the $|1\rangle\leftrightarrow|3\rangle$ transition. The spontaneous decay rate from the excited state to the ground state is Γ, which is $2\pi\times6$ MHz for the $5P_{3/2}$ state in Rb. Thus, the Λ system is formed by the $F=2\leftrightarrow F'=1\leftrightarrow F=1$ hyperfine levels. Actually, there is a second Λ system formed by the $F=2\leftrightarrow F'=2\leftrightarrow F=1$ levels, from which the lasers are detuned by an additional 157 MHz.

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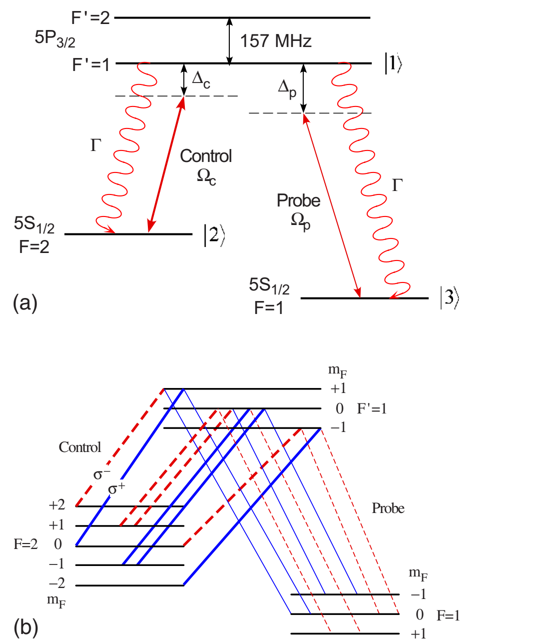

FIG. 1. (Color online) (a) Three-level Λ system in the D_2 line of ^{87}Rb. (b) Sublevels coupled by circular polarization in the presence of a magnetic field $-\sigma^+$ (solid lines) and σ^- (dashed lines).

The second system is important when accounting for optical pumping by the control laser.

From a density matrix analysis of the system [17,18], the absorption of the weak probe is given by $-\mathrm{Im}(\rho_{13}\Gamma/\Omega_p)$, where ρ_{13} is the induced polarization on the $|1\rangle \leftrightarrow |3\rangle$ transition. In the weak probe limit, all the atoms get optically pumped into the $|3\rangle$ state, so that $\rho_{33}\approx 1$ and $\rho_{22}\approx 0$. The steady-state solution of the density matrix equations yields (to first order in Ω_p and all orders in Ω_c),

$$\rho_{13} = -\frac{i\Omega_p/2}{\Gamma - i\Delta_p + i\dfrac{|\Omega_c/2|^2}{\Delta_p - \Delta_c}}. \tag{1}$$

The pole structure of this equation shows that there will be a zero in the absorption when $\Delta_p = \Delta_c$, which is the phenomenon of EIT. For a fixed value of Δ_c, probe absorption as a function of Δ_p will show two peaks (the usual Autler-Townes doublet) at the locations of the dressed states created by the control laser, whose separation is the effective Rabi frequency $\sqrt{\Omega_c^2+\Delta_c^2}$.

To account for the thermal motion of atoms in room-temperature vapor, one must correct the above expression for the Doppler shift in frequency seen by a moving atom, and then average over the one-dimensional Maxwell-Boltzmann distribution of velocities. The velocity-dependent polarization is given by

$$\rho_{13}(v) = -\frac{i\Omega_p/2}{\Gamma - i(\Delta_p - kv) + i\dfrac{|\Omega_c/2|^2}{\Delta_p - \Delta_c}}, \tag{2}$$

where $k=2\pi/\lambda$ is the photon wave vector. In recent work [8], we have shown that the effect of such thermal averaging is to actually reduce the linewidth of the EIT dip. In other words, the moving atoms fill in the transparency band such that the remaining EIT dip is much smaller than the Autler-Townes splitting for stationary atoms. We observed a linewidth of only $\Gamma/4$ for $\Omega_c = 8\Gamma$ and $\Delta_c = 0$.

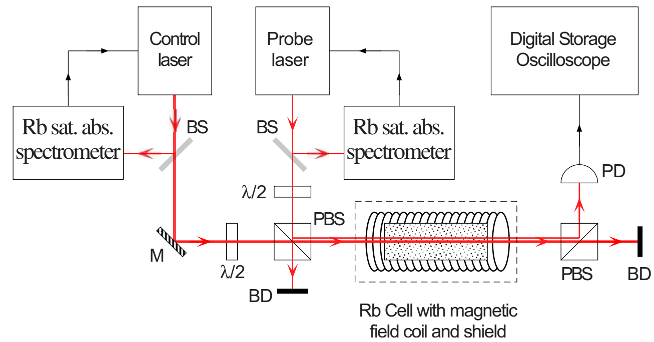

FIG. 2. (Color online) Schematic of the experiment. The probe and control are shown as nonoverlapping only for clarity. Figure labels: BS, beam splitter; $\lambda/2$, halfwave retardation plate; PBS, polarizing beam splitter; BD, beam dump; M, mirror; PD, photodiode.

Now consider what happens when we apply a longitudinal magnetic field. Each magnetic sublevel $|F,m_F\rangle$ will be shifted by an amount $\mu_B g_F m_F B$, where $\mu_B = 1.4$ MHz/G is the Bohr magneton, g_F is the Landé g factor of the level, and B is the magnetic field. The shifted sublevels are shown schematically in Fig. 1(b). Since the probe and control lasers are linearly polarized, and the quantization axis set by the magnetic field is along their propagation direction, the two beams will be seen in the atom's frame as being circularly polarized. Eight Λ subsystems are created, coupled by different combinations of $\sigma^\pm$ probe and $\sigma^\pm$ control. Each of these subsystems is shifted in frequency. We will see later that the combined effect of these eight subsystems is to create three transparency dips of reduced linewidth.

Before we turn to the results, we highlight one interesting experimental technique that we have adopted. In normal EIT experiments, probe absorption is measured while the probe laser is scanned; instead we lock the probe laser to one transition, and monitor its absorption while scanning the control laser. This method [6] makes the probe absorption "Doppler free" in the sense that the absorption remains flat (corresponding to absorption by one velocity group) until it is modified by the control laser. Thus, the probe absorption appears on a flat background, and does not have an underlying Doppler profile that may cause undesirable peak-pulling effects.

The experimental schematic is shown in Fig. 2. The probe and control beams are derived from two home-built frequency-stabilized diode laser systems [19] operating on the 780 nm D_2 line of Rb. Part of the output of each laser is sent into two Rb saturated-absorption spectrometers. The probe laser is locked to the $F=1 \rightarrow F'=1$ hyperfine transition using fm modulation spectroscopy, while the control laser is scanned around the $F=2 \rightarrow F'=1$ transition. The linewidth of the lasers after stabilization is on the order of 1 MHz. The two beams are about 2 mm in diameter and have powers of 50 μW (probe) and 500 μW (control). The beams copropa-

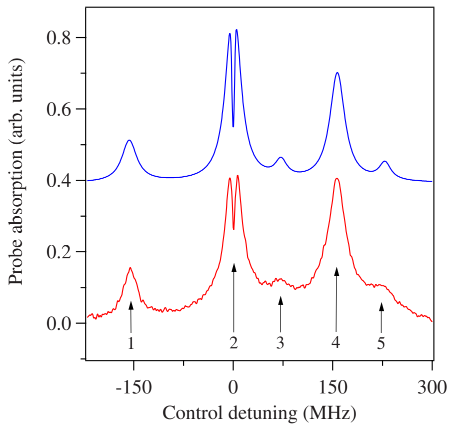

FIG. 3. (Color online) EIT in ^{87}Rb at room temperature with $B=0$. The lower trace is the measured spectrum showing five broad peaks and a narrow EIT dip in the center of peak 2. The broad peaks are due to deviations from the Maxwell-Boltzmann velocity distribution arising from velocity-dependent optical pumping by the control laser. The calculated spectrum shown in the upper trace (with $\Delta_p=0$ and $\Omega_c=10$ MHz) takes into account such optical pumping and is able to reproduce the five peaks with the EIT dip in peak 2.

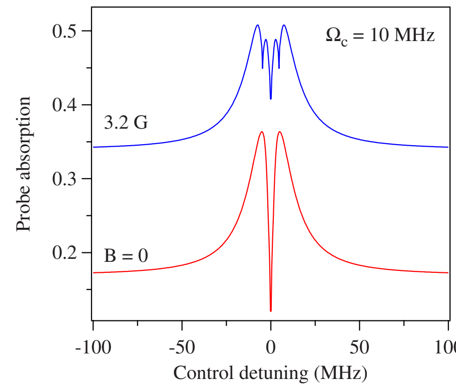

FIG. 4. (Color online) Calculated spectrum for $B=0$ (lower trace) and $B=3.2$ G (upper trace).

gate through a room-temperature vapor cell (5 cm long) with orthogonal linear polarizations. The cell has a solenoidal coil that can produce fields up to 5 G. The whole assembly has a magnetic shield [20] to shield against stray external fields.

A typical probe absorption spectrum vs control detuning with no magnetic field is shown in the lower trace of Fig. 3. The most important feature is the narrow EIT dip appearing at $\Delta_c=0$. The linewidth, defined as the full width at half-maximum, is only 4.5 MHz ($=0.75\Gamma$). The probe absorption appears on a flat background, as expected, but there are five broad peaks. As explained in our earlier work [8], these peaks are due to velocity-dependent optical pumping by the control laser, which causes the velocity-dependent population of $F=1$ atoms to deviate from the Maxwell-Boltzmann distribution. There are two velocity classes that get optically pumped into the $F=1$ level—those for which the control is resonant with the $F'=1$ level, and those for which the control is resonant with the $F'=2$ level (which is 157 MHz higher). For example, when $\Delta_c=0$, the two optical pumping peaks appear at $v=0$ and $v=-122$ m/s.

A calculated spectrum taking into account the effects of optical pumping by the control laser is shown in the upper trace of Fig. 3. The calculation is for $\Delta_p=0$ and $\Omega_c=10$ MHz. The degree of optical pumping is taken to be proportional to the photon-scattering rate in the atom's frame, and it is further assumed that there is complete optical pumping when the control is on resonance. The calculation also incorporates the effect of the second Λ system formed by the $F=2\leftrightarrow F'=2\leftrightarrow F=1$ levels, which is detuned by 157 MHz [see Fig. 1(a)]. The calculated spectrum reproduces the five optical pumping peaks quite well, and shows that only peak 2 will have the EIT dip. Peaks 3 and 5 are due to probe transitions to the $F'=0$ level, which is 72 MHz below the $F'=1$ level. Interestingly, the detuned EIT of the second Λ system shows up in the calculated spectrum as a slight asymmetry of the two lobes of peak 2, which appears in the measured spectrum as well. We thus see that a detuned EIT channel can have an effect on the resonant EIT dip even if the detuning is as large as 31Γ. As we will see below, the presence of nearby detuned EIT channels is the basis of the linewidth reduction in the presence of a magnetic field.

We now consider the effect of a longitudinal magnetic field in more detail. From the energy-level scheme presented in Fig. 1(b), eight Λ subsystems will be formed, each of which is shifted slightly from the line center. The combined effect of these is seen from the calculated spectrum in Fig. 4 (with $\Delta_p=0$ and $\Omega_c=10$ MHz). In the absence of a field, there is a single EIT dip at the line center. When a field of 3.2 G is applied, three EIT dips appear, one at the line center and two symmetric sidebands. All three dips are narrower than the original dip.

The underlying cause of the narrowing can be understood by considering the EIT dips due to the individual subsystems, as shown in Fig. 5. For illustration, we consider the four subsystems with $m_F=0$ in the excited state. Two of the subsystems (dashed curves) cause transparency at the line center, while the other two (dotted curves) cause off-center transparency dips. Each transparency window is filled in by the detuned resonances so that the resultant linewidth is con-

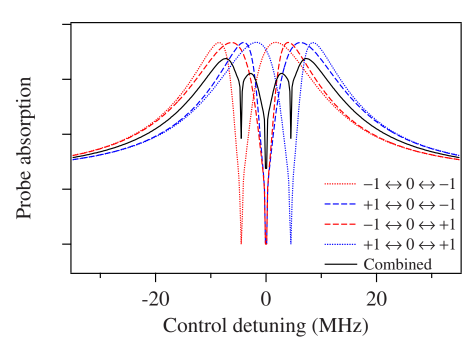

FIG. 5. (Color online) Calculated spectra with $B=3.2$ G for different subsystems showing how the shifted EIT resonances fill in the transparency window. The four subsystems considered are all with $m_F=0$ in the excited state, and are labeled according to the m_F's coupled by the probe and control, respectively [see Fig. 1(b)]. The first and last subsystems (dotted curves) reduce the transparency width for the middle subsystems (dashed curves), and vice versa. This is seen in the combined spectrum (solid curve).

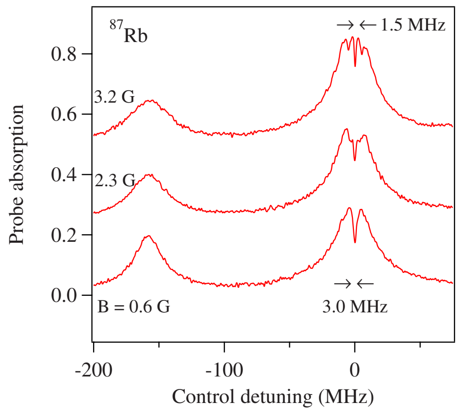

FIG. 6. (Color online) Splitting of EIT resonance in ^{87}Rb with increasing magnetic field. Three distinct dips appear at a field of 3.2 G and the linewidth of the central dip is significantly reduced.

siderably smaller, as seen from the combined spectrum (solid curve). As expected, there is also a reduction in the scale of each transparency due to the shifted resonances. This mechanism is basically the same as the narrowing that happens when one does thermal averaging in hot vapor [8]. In that case, the moving atoms see a detuned EIT resonance, which fills in the transparency window so as to reduce the final EIT linewidth.

The same behavior is observed experimentally, as seen from Fig. 6. As the field is increased, two side lobes begin to appear on the central EIT dip which are equally separated from the line center. The side lobes become nonoverlapping when the field reaches a value of 3.2 G. The linewidth of the central EIT dip is already 3 MHz for a field of 0.6 G, which is narrower than the 4.5 MHz linewidth for zero field (Fig. 3). It further narrows to 1.5 MHz when the field is 3.2 G. There is also a decrease in the depth of the transparency, as expected from the calculation. The optical pumping due to the control laser changes as the field is increased, hence the peak at −157 MHz varies in height.

In the other isotope of Rb, ^{85}Rb, the hyperfine levels forming the Λ system are $F=3 \leftrightarrow F'=2 \leftrightarrow F=2$. Thus there are 16 Λ subsystems that are formed in the presence of a magnetic field, each of which is shifted by an amount that depends on the Landé g factor of the levels. A calculation similar to the one in Fig. 4 shows that their net effect is to create five EIT dips (a central dip with two pairs of sidebands). Such fivefold splitting of the spectrum is seen in Fig. 7, when the field reaches a value of 3.1 G. The optical pumping peaks are present as in the case of ^{87}Rb, but their loca-

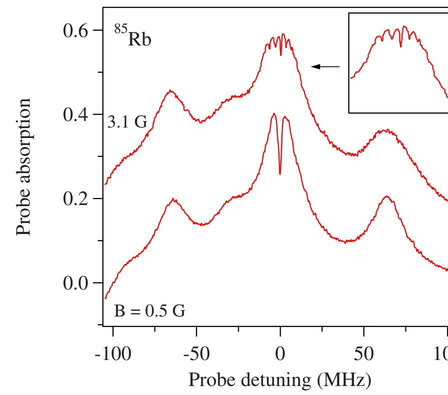

FIG. 7. (Color online) Splitting of EIT resonance in ^{85}Rb with increasing magnetic field. Five dips appear in this case, as seen from the expanded view in the inset, because of the upper level having $F'=2$. Note also that it is the probe laser that is being scanned.

tions are now at −92, −63, −29, 0, and 63 MHz [21]. The spectrum also shows the advantage of scanning the control laser over scanning the probe laser; in this case there is an underlying Doppler background because the spectrum is obtained by scanning the probe frequency. But the important feature of linewidth reduction of the central EIT dip is still seen clearly.

In conclusion, we have demonstrated a significant reduction in the linewidth of the EIT resonance in room-temperature Rb vapor with the application of a small longitudinal magnetic field. The unperturbed linewidth is already subnatural ($<\Gamma$) due to Doppler averaging. The presence of the magnetic field then Zeeman shifts the sublevels to create multiple three-level subsystems, which causes the EIT dip to split into narrower resonances symmetrically about the line center. Narrow EIT resonances are important for high-resolution spectroscopy and tight locking of lasers. In addition, the narrow feature implies that the anomalous dispersion near the resonance is more pronounced, which could be important in applications of EIT such as slowing of light and nonlinear optics. The technique also provides a way of creating multiple EIT resonances with controlled spacing and linewidth.

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