Subnatural linewidth in a strongly-driven degenerate two-level system

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We observe linewidths below the natural linewidth for a probe laser on a degenerate two-level \( F \rightarrow F \) transition, when the same transition is driven by a strong control laser. We take advantage of the fact that each level of the transition is made of multiple magnetic sublevels, and use the phenomenon of electromagnetically induced transparency (EIT) or absorption (EIA) in multilevel systems. Optical pumping by the control laser redistributes the population so that only a few sublevels contribute to the probe absorption, an explanation which is verified by a density-matrix analysis of the relevant sublevels. We observe more than a factor of 3 reduction in linewidth in the \( D_2 \) line of Rb in room-temperature vapor. Such subnatural features vastly increase the scope of applications of EIT, such as high-resolution spectroscopy and tighter locking of lasers to atomic transitions, since it is not always possible to find a suitable third level.

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1. Introduction

The natural linewidth of a two-level \( F \rightarrow F \) transition appears as a fundamental limit to the accuracy with which the transition can be used, either for frequency measurement or as a frequency reference for locking a laser. The natural linewidth is determined by the (inverse of the) lifetime of the excited level. In three-level (and other multilevel) systems, it is now well known that a strong control laser on an auxiliary transition can be used to modify the effective lifetime of the excited level; hence the linewidth of the transition being probed by a weak laser can become subnatural. The effect, called electromagnetically induced transparency (EIT) or absorption (EIA) [1,2], arises due to the AC-Stark shift of the levels caused by the control laser (\textit{creation of dressed states} [3]), and subsequent quantum interference of the absorption pathways to these dressed states [4]. The subnatural linewidth observed in these multilevel systems [5,6] leads to applications in high-resolution spectroscopy [7] and sub-Doppler laser cooling [8], while the anomalous dispersion near the resonance has applications in slowing of light [9] and quantum information processing.

In this work, we show that such subnatural linewidth can also be observed in a two-level \( F \rightarrow F \) transition, i.e. a (degenerate) two-level system where both the control and probe drive the same transition and no third level is involved. We take advantage of the fact that each level of the degenerate transition is made of multiple magnetic sublevels. Optical pumping by the control laser then causes the population to redistribute among the sublevels, and only a few sublevels contribute to probe absorption. The coherences induced by the control laser cause a subnatural resonance exactly at line center. This explanation is borne out by a theoretical density-matrix analysis of the relevant sublevels. Our experiments are done in the \( 5S_{1/2} \rightarrow 5P_{3/2} D_2 \) line of Rb, where we observe more than a factor of three reduction below the natural linewidth. Interestingly, we observe these narrow resonances with room temperature vapor, where the Doppler width is typically 100× larger than the natural linewidth.

The ground state of Rb (and other alkali atoms) consists of two hyperfine levels, thus there are two sets of transitions starting from this state. Though the subnatural feature shows up for both sets of transitions, it appears as enhanced absorption (EIA) in one case and enhanced transmission (EIT) in the other. This is because the dominant transition for the upper-level set is the closed \( F \rightarrow F + 1 \) transition (with a larger number of magnetic sublevels in the excited state), while it is \( F \rightarrow F - 1 \) for the lower-level set (with a smaller number of magnetic sublevels in the excited state). Thus, the relevant sublevels form an \textit{N}-type system for the upper-level transition and a \textit{A}-type system for the lower-level transition. The density-matrix calculation of the simplified sublevel structure reproduces this difference between the two sets.

The subnatural features we observe in our work are also to be contrasted with the related phenomenon of coherent-population trapping (CPT). CPT is well known both in \textit{A}-type three-level systems [10,11] and degenerate two-level systems [12]. The linewidth of the narrow feature in CPT is extremely narrow compared to the linewidth of the excited state because it is limited only by the decoherence rate between the two ground levels. This phenomenon relies on the use of \textit{phase-coherent} control and probe beams to drive the atoms into a dark non-absorbing state. In degenerate two-level systems, this phase coherence is achieved by using a single laser to generate both beams. The two beams usually have roughly equal intensities as both are required to drive the atoms into the dark state. Since CPT is a ground-state coherence phenomenon, it is used, for example, for precision

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1 Visiting from Ecole Normale Supérieure de Lyon.
spectroscopy of the ground hyperfine interval in atomic clocks [13].
These experiments benefit by the use of vapor cells filled with buffer
gas or with paraffin coating on the walls, which increase the ground-
cohere time but also shift or broaden the optical transition.
Moreover, the relevant natural linewidth in these cases is the inverse
of the lifetime of the upper ground level, which can be quite long
because the transition is electric-dipole forbidden. Significantly, the
scan axis in CPT experiments is the Raman detuning between the two
lasers from the two-photon resonance condition, and not the optical
frequency of the probe laser. Thus, if the control laser was detu
from its optical resonance, it will not affect the Raman resonance
condition for CPT, but it will shift the resonance location for EIT.
In summary, our EIT experiments (i) use a weak probe laser; (ii) can be
used for precision spectroscopy on the excited state[7]; (iii) use pure
vapor cells; and (iv) have a scan axis (showing the subnatural feature)
that is the optical frequency of the phase-independent probe laser.

2. Experimental set-up

The experimental set-up is shown schematically in Fig. 1. The control
and probe beams are derived from two independent home-
built diode laser systems operating on the 780 nm D2 line of Rb [14].
The linewidth of the lasers after feedback stabilization is about 1 MHz.
The beams are elliptic and have a size of 2 mm. The Raman beam
is locked to a hyperfine transition using saturated-absorption
spectroscopy (SAS) in a vapor cell. The control beam is scanned
on the same transition. The two beams have orthogonal circular
polarizations ($\sigma^+$ and $\sigma^-$) and co-propagate through a cylindrical
vapor cell of dimensions 25-mm diameter $\times$ 50-mm length. The cell
has a multilayer magnetic shield that reduces the stray fields to below
1 mG. The two laser beams are mixed and separated using polarizing
beam splitter cubes (PBS), and the probe beam is detected with
a photodiode. The individual beam powers are controlled using
halfwave retardation plates before the PBS’s. We have shown earlier
[15] that the use of co-propagating beams eliminates crossover
resonances, and that by scanning the control laser while keeping the
probe fixed makes the signal appear on a Doppler-free background.

3. Results and discussion

The first set of experiments was done for transitions starting from the
upper ground level in $^{87}$Rb, i.e., on the closed $F=2 \rightarrow F=3$ transition. The results for a probe power of 8 $\mu$W and control power of 150 $\mu$W are shown
in Fig. 2. The spectrum shows a broad (20 MHz wide) transparency
peak as the control laser is scanned. This is the usual resonance occurring
due to EIT and saturation effects seen in pump-probe spectroscopy [15].
Exactly at line center, a narrow EIA dip (corresponding to enhanced
absorption) appears. The full-width-at-half-maximum (FWHM) of the
narrow resonance is only 1.8 MHz compared to the natural linewidth
of 6 MHz. The subnatural feature is robust and the FWHM remains less
than 3 MHz (0.5 $\Gamma$) with increase in control power to 250 $\mu$W. But as the control power is increased, the depth of the resonance and its signal-
to-noise ratio increases. For comparison, a typical SAS spectrum (taken
with counter-propagating beams) is shown in the figure inset. With
optimal powers in the pump and probe beams, the linewidth is 6.6 MHz
(1.1 $\Gamma$).

To understand this line shape theoretically, we consider the magnetic
sublevel structure shown in Fig. 3. For the $2 \rightarrow 3$ transition, there are 5 and
7 sublevels respectively. Optical pumping by the circularly-polarized
control will transfer all the population into the third ground sublevel,
as shown in Fig. 3(a). If we therefore ignore the other sublevels, we have a
V-type system formed by the $m_F=+3$ and $m_F=-2$ sub-
levels. Dressing of the $m_F=+2$ and $m_F=-3$ sublevels by the strong
control laser will cause the usual transparency resonance (EIT) for the
weak probe laser. Now consider that the control is also going to dress the
$m_F=0$ and $m_F=+1$ sublevels, forming effectively an N-type system
[16,17]. The additional coherences induced by this is what causes the
narrow EIA resonance.

We have done a density-matrix analysis [18] of this simplified
sublevel structure to confirm the above explanation. In this approach,
probe absorption is proportional to $\text{Im}(\rho_{11})$, where $|1\rangle$ and $|2\rangle$ are the
two levels coupled by the probe laser. The coupling beams are
weighted by their respective Clebsch–Gordan coefficients. The
calculation takes into account the velocity-dependent Doppler shift
for the velocity distribution in room temperature vapor. In Fig. 3(b),
we show the calculated spectrum considering the N-type system

![Fig. 1. Schematic of the experiment with independent control and probe lasers. Figure key: BS — beam splitter, $\lambda/2$ — halfwave retardation plate, $\lambda/4$ — quarterwave retardation plate, M — mirror, PBS — polarizing beamsplitter cube, PD — photodiode.](image)

![Fig. 2. Subnatural EIA resonance for upper-level transitions obtained with the probe laser locked to the $F=2 \rightarrow F=3$ transition and control laser scanning across the same transition. The inset shows a typical SAS spectrum, which has a linewidth of 1.1 $\Gamma$.](image)
formed by the $m_F=0$ and $+2$ sublevels. The Rabi frequency of the control laser is taken to be 6 MHz, which corresponds to the experimental power if we assume that the entire power is spread uniformly over the beam size. To account for the finite linewidth of the control laser, we assume that the ground sublevels decohere at a rate of 1 MHz. This is not a limiting assumption, since the simulation with zero decoherence rate (dotted curve) shows no appreciable change in linewidth of the central dip. There are no other adjustable parameters. The calculated spectrum reproduces the features of the observed spectrum shown in Fig. 2, with a broad EIT peak and a narrow EIA dip at line center. We have verified that the EIA dip disappears if we do not consider the dressing of the $m_F=+1$ sublevel. Furthermore, the depth of the EIA resonance increases with increasing Rabi frequency of the control, exactly as observed experimentally. The calculation also shows that the width of the EIA dip becomes smaller at smaller control powers, but observing linewidths below 1.5 MHz is experimentally challenging because the probe laser itself has a linewidth of 1 MHz.

The next set of experiments was done for transitions starting from the lower ground level in $^{87}$Rb, i.e., with the lasers on the closed $F=1 \rightarrow F=0$ transition. The spectrum obtained with a probe power of 8 μW and a smaller (compared to the previous set) control power of 80 μW is shown in Fig. 4(a). In this case, the measured spectrum has a central transparency peak surrounded by broad enhanced absorption wings. The EIT peak at line center is subnatural, with a linewidth of only 2.4 MHz (0.4 $\Gamma$). For comparison, we again show in the inset a typical SAS spectrum taken with optimal pump and probe powers. The linewidth of 12 MHz is 5 times larger than the one for the control laser optically pumps the population into the $m_F=0$ and $+2$ sublevels. The Rabi frequency of the control laser is taken to be 6 MHz, which corresponds to the observed SAS spectrum for the same transition. (b) Calculated spectrum for the $\Lambda$-type system shown in the inset.

As before, the features of the measured spectrum can be understood theoretically. In this case, the sublevel structure is quite simple, with 3 sublevels in the lower level and 1 sublevel in the upper level. The circularly-polarized beams couple these sublevels to form a $\Lambda$-type system, as shown in the inset of Fig. 4(b). The calculated spectrum, using a Rabi frequency of 4.4 MHz (because the control power is a factor of 2 smaller) and taking into account thermal averaging, reproduces the features of the observed spectrum including the enhanced-absorption wings. This can be understood as follows. Off resonance, the strong control laser optically pumps the population into the $m_F=+1$ sublevel, which causes increased probe absorption. As the control comes into resonance, there are additional induced coherences, which causes the EIT resonance. It is well known that in $\Lambda$-type systems the EIT resonance can be subnatural [4,5]. The calculated spectrum has a width similar to the measured one.

As in the case of upper-level transitions, the FWHM of the central resonance remains below 3 MHz even with a control power of 250 μW, while its signal-to-noise ratio increases. We are also able to go to lower control powers of about 40 μW and still see a prominent resonance. But the linewidth does not decrease much, probably again because of the 1-MHz linewidth of the probe laser.

In the above experiments, we have considered the closed transition in each set because it is an almost perfect realization of a two-level system, albeit degenerate. The calculations could be done without worrying about the presence of the other levels. However, this is not true for open transitions because we have to consider the effect of optical pumping into the closed transition. Still, experimentally we find the same behavior for the open transitions also. The results for the $F=2 \rightarrow F=2$ and $F=1 \rightarrow F=1$ transitions are shown in Fig. 5. The control powers are 150 μW and 40 μW, respectively. As before, we see enhanced absorption for the upper-level transition [shown in (a)] and enhanced transmission for the lower-level transition [shown in (b)]. The line shapes and widths
In summary, we have observed linewidth reduction below the natural linewidth in a two-level \( F \rightarrow F' \) transition, when a strong control laser is applied to the same transition. We take advantage of the presence of multiple magnetic sublevels in each level and the phenomenon of electromagnetically induced transparency or absorption, a phenomenon that is well studied three-level systems but not in two-level systems. This increases the range of applications of EIT and EIA, such as high-resolution spectroscopy and tight locking of lasers, since it is not always possible to find a suitable third level.

We observe these subnatural resonances in the D\(_2\) line of \(^{87}\text{Rb}\) using room-temperature atoms in a vapor cell. There are two sets of hyperfine transitions starting from the two ground hyperfine levels, and we observe the subnatural feature for both sets. However, it appears as an enhanced-absorption dip for upper-level transitions, and as an enhanced-transparency peak for lower-level transitions. This difference can be understood from the differences in the number of magnetic sublevels. As is the case with EIT experiments in three-level systems, the subnatural features appear exactly at line center (i.e., with no systematic offset) as long as the control laser is also at line center. Thus, the probe laser can be stabilized with smaller statistical uncertainty on an atomic transition. In effect, the control laser modifies the environment for the probe laser so that it sees a narrower linewidth for a dipole-allowed transition, without involving an additional third level.

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