Coherent population trapping (CPT) versus Electromagnetically induced transparency (EIT)

Sumanta Khan, M. P. Kumar, Sapam Ranjita Chanu, Vineet Bharti, and Vasant Natarajan
Department of Physics, Indian Institute of Science, Bangalore 560 012, India

We discuss the differences between two well-studied and related phenomena—coherent population trapping (CPT) and electromagnetically induced transparency (EIT). We show experimentally that one does not observe EIT in a Rb vapor cell filled with buffer gas, a kind of cell that is used commonly in CPT experiments because it results in significant linewidth reduction of the resonance.

Keywords: Electromagnetically induced transparency; Coherent population trapping; Coherent control; Quantum optics

I. INTRODUCTION

The phenomenon of Coherent Population Trapping (CPT), reviewed by Arimondo in Ref. 1, and the phenomenon of Electromagnetically Induced Transparency (EIT), reviewed in Refs. 2 and 3, are two sides of the same coin. Both phenomena have been studied for a long time, particularly in three-level Λ-type systems. The physics underlying the two phenomena are related, but they are also distinct in many ways. The aim of this article is to highlight the differences between the two, in part because many researchers in the field do not appreciate these differences. Some of the confusion arises due to the interchangeable use of the words EIT and CPT, for what are really CPT processes.

CPT was first observed as a decrease in the fluorescence emission from Na atoms in a vapor cell 4. It was understood to arise from the fact that the atoms were being optically pumped into a dark non-absorbing state by the excitation beams. In other words, the atoms were being coherently trapped in the dark state, hence the name coherent population trapping. The dark state was created by destructive interference between excitation pathways from two stable levels to a common excited level. The three levels form a classic Λ-type system, as shown in Fig. 1. It is customary to call the laser driving the |1⟩ ↔ |3⟩ transition as the probe laser, and the one driving the |2⟩ ↔ |3⟩ transition as the control laser. Both are usually electric-dipole-allowed transitions; hence the transition |1⟩ ↔ |2⟩ is forbidden. The detunings are labeled by Δ’s, the powers by the respective Rabi frequencies Ω’s, and the spontaneous decay rates by Γ’s. Γ_{31} and Γ_{32} (i.e. for the allowed transitions) are of order few MHz, while Γ_{12} for the forbidden transition is nominally 0. In reality, there is decoherence between the levels due to collisions, laser linewidth 5, etc. It is important to realize that the two lasers have to be phase coherent so that the dark superposition state can be formed.

EIT works on a slightly different principle. The phenomenon is usually studied in the regime where the control laser is strong and the probe laser is weak (Ω_p ≪ Ω_c). Under these conditions, the control laser shifts the energy levels of the atom away from line center through the AC Stark effect, which can also be understood as the creation of new dressed states of the coupled atom-photon system 6. The shift is equal to the Rabi frequency of the control laser. The absorption of the probe laser splits into a classic Autler-Townes doublet (with a splitting equal to the control Rabi frequency), and shows enhanced transparency at line center—a transparency induced by the control laser. Hence the name electromagnetically induced transparency. Thus, EIT can be seen as a modification of the properties of the medium by the strong control laser, while the weak probe laser only plays the role of measuring this modification. Generally, the probe laser in EIT experiments is derived from a phase independent laser.

The above analysis shows that both EIT and CPT are two-photon processes, because the transitions involve two different levels. However, in CPT both the probe and control photons are equally important. Because the photons are phase coherent, the amplitudes of their excitation pathways add, which leads to destructive interference in the absorption. However, in EIT the probe photon is not directly involved in the transparency, and the transparency is entirely created by the strong control laser. The role of quantum interference is that of the decay pathways from the dressed states created by the control laser 7.

With these basic differences in mind, let us now contrast the two phenomena in terms of various experimental
parameters.

1. **Scan axis.** The first and foremost difference between EIT and CPT is the scan axis. In CPT, this is the relative detuning between the two beams. If the phase coherence is set by an acousto-optic modulator (AOM), the scan axis will be the frequency of the AOM, which is usually of order few MHz. On the other hand, the scan axis in EIT is the frequency of the phase-independent probe laser. If the probe transition is in the optical regime, the frequency is of order $10^{15}$ Hz, or 8 orders of magnitude larger than that for CPT.

2. **Power in the two beams.** As mentioned before, both beams play an equally important role in CPT, while EIT is studied in the regime where the control is strong and the probe is weak. This leads to an important difference—namely, that the powers (and hence intensities) in the two beams are roughly equal for CPT, while the power in the probe beam is negligibly small for EIT. This also has implications for the theoretical density-matrix analysis in the two cases. EIT is analyzed under the approximation of neglecting higher-order terms in the probe intensity, whereas this approximation is not valid for CPT. In addition, the quantity of interest in EIT is the term $\rho_{13}$ which gives the probe absorption, while in CPT it is $\rho_{33}$ which gives the population in the upper state.

3. **Subnatural resonance—the relevant natural linewidth $\Gamma$.** The discussion of the scan axis brings us to the question of what defines whether the feature is subnatural or not. First, note that the error signal from any feature can be fed back to lock the frequency of the scanning device. In CPT experiments, it is the AOM at the difference frequency between the two lower levels. The relevant natural linewidth is therefore the linewidth of transition between the two ground levels, which, as mentioned before, is close to zero because the transition is electric-dipole forbidden. The linewidth of the upper level does not enter the picture. As an example, we consider the observation of a resonance linewidth of 42 Hz for coherent dark resonances in a Cs vapor cell filled with buffer gas. The resonance is on the ground hyperfine splitting of $^{133}$Cs, which is the well-known clock transition at 9.1 GHz used in the SI definition of the second. The experiments were done on the $D_2$ line of Cs, but the 5 MHz linewidth of the upper state does not enter the picture. Nowhere in the above work do the authors call their resonance *subnatural*, because it is well known that the natural linewidth of the clock transition is well below 1 Hz. Similarly, the phase-locked lasers used in the above study have a linewidth of order 1 MHz. This does not prevent them from seeing a 42-Hz feature because they are looking for a beat signal between two phase-coherent lasers, which can be much narrower than the linewidth of the laser. As a consequence, the CPT phenomenon can be used for precision spectroscopy on the ground levels.

On the other hand, we have shown that the narrow features of EIT are really *subnatural* and can be used for high-resolution spectroscopy of the upper level. This is because the scan axis is the optical frequency of the probe laser, and the relevant natural linewidth is the linewidth of the upper level. In the case of the Rb $D_2$ line used in our study, the upper level has a linewidth of 6 MHz. Therefore, any feature that is narrower than 6 MHz would be called subnatural. The narrowest feature that we have reported on the $D_2$ line of Rb is 0.85 MHz or $\Gamma/7$. This corresponds to a $Q$ of $4.5 \times 10^5$, which is better than the $Q$ of $2.2 \times 10^5$ for the CPT experiment on the clock transition in Ref.

4. **Fluorescence vs Absorption.** One important consequence of the fact that CPT results from the creation of a dark state is that there is a concomitant decrease in the fluorescence from the cell, i.e. it becomes dark. Recall that the first observation of CPT was the appearance of a dark region in the fluorescence from a Na vapor cell. In that study, an inhomogeneous magnetic field was applied along the axis of the cell, so that the dark state was created only in a small region. Thus the phenomenon was seen as a dark line in a bright cell. By contrast, in EIT, the strong control laser is always being absorbed (and atoms are fluorescing), and the induced transparency is seen only in the absorption signal of the weak probe laser. Therefore, to first order, there will be no change in the fluorescence whether the probe laser is on or off.

5. **Effect of buffer gas.** Because CPT is a ground-state coherence phenomenon, any technique that increases the coherence time will give a narrower linewidth. One of the most common methods is to use a buffer gas in the vapor cell, typically a few torr of a gas like Ne or N$_2$. The CPT experiment on the clock transition in Ref. was done in a vapor cell filled with N$_2$ buffer gas. On the other hand, the use of such cells for EIT experiments actually kills the signal (see the experimental results presented in the next section). This is because the buffer gas broadens the normal probe-absorption signal due to collisions, and swamps any modification due to the control.

6. **Effect of detuning from the upper level.** The upper level in CPT plays the role of causing decoherence of the dark state. Therefore, detuning from the upper state narrows the linewidth. Of course, there is a simultaneous reduction in signal
strength, but this can be compensated by increasing the power. Thus, many CPT experiments are done with a detuning of several linewidths from the excited state. Note that the CPT resonance still occurs at the same relative detuning between the two beams, which is the point at which the two-photon Raman resonance condition is satisfied. On the other hand, detuning the control laser from the upper level in EIT causes the resonance to shift within the absorption profile of the probe laser. The resonance again appears where the probe detuning matches the control detuning, but the detuned lineshape is very different.

II. RESULTS AND DISCUSSION

Most of the above points are well-documented in the vast literature on this subject, though not always in one place. However, one experimental result that is not presented in any paper is the difference between buffer-gas filled cells and pure cells. Therefore, we present below experimental results comparing EIT and CPT in these two kinds of cells. The experiments are done on the $D_2$ line ($5S_{1/2} \leftrightarrow 5P_{3/2}$ transition) in $^{87}$Rb. There are two hyperfine levels ($F = 1, 2$) in the ground state and four hyperfine levels ($F' = 0, 1, 2, 3$) in the excited state. The $\Lambda$ system is formed using the two ground levels and the excited state. The $\Lambda$ system is tuned by the control laser, which increases population in the excited state.

The experimental set-up for the EIT experiments is shown schematically in Fig. 2. The control and probe beams are derived from two independent home-built diode laser systems [12]. The linewidth of the lasers after feedback stabilization is about 1 MHz. The beams are elliptic and have a $1/e^2$ diameter of 2 mm $\times$ 3 mm. The control laser is locked to the $2 \leftrightarrow 2$ transition using saturated-absorption spectroscopy in a (pure) Rb vapor cell. The total power entering the cell 1.2 mW. The probe laser is scanned around the $1 \leftrightarrow 2$ transition with a power of 0.15 mW. The two beams have orthogonal linear polarizations (lin $\perp$ lin) 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.

Two kinds of cells were used for the experiments—one that contained pure elemental Rb with both isotopes, $^{85}$Rb and $^{87}$Rb, in their natural abundances; and the second that contained $^{87}$Rb with 20 torr of Ne as buffer gas. The experimental results for EIT are shown in Fig. 3. Let us first consider the probe-absorption spectrum in a buffer-gas filled cell [the top trace of Fig. 3(a)]. The open circles show the measured spectrum, while the solid line is a fit to a Gaussian curve. The photodiode trans-impedance gain is adjusted so that the signal height is roughly equal to the percentage linear absorption through the cell, which is about 3% in this case. The Gaussian curve describes the spectrum very well, but the width is 960 MHz. The width expected from the Maxwell-Boltzmann distribution for Rb vapor at 300 K is 516 MHz [13]. The increase by almost a factor of 2 is due to collisional broadening from the buffer-gas molecules in the cell. This broadening is also the reason that a buffer-gas filled cell cannot be used for saturated absorption spectroscopy—it gives no hyperfine spectrum, as we have verified.

FIG. 2. (Color online) Schematic of the experiment for EIT with independent control and probe lasers. Two kinds of cells were used—either pure with both isotopes, or containing $^{87}$Rb with 20 torr of Ne buffer gas. Figure key: $\lambda/2$ – halfwave retardation plate, PBS – polarizing beamsplitter cube, PD – photodiode.

It is more interesting to see what happens when the control beam is turned on. The results, plotted in the lower trace of Fig. 3(a), show that there is no sign of EIT. Instead, the absorption dip becomes a bit wider and, with the same photodiode gain, deeper by a factor of 6. This is because of optical pumping by the strong control laser, which increases population in the $F = 1$ level and therefore increases probe absorption. By contrast, a pure cell shows an EIT peak (at line center), as shown in Fig. 3(b). The scan range is much smaller so that the nearby peak from the other isotope ($^{85}$Rb) is not seen. The broad probe-absorption dip is modified by narrower (~ 80 MHz wide) optical-pumping dips whenever the control laser is resonant with a hyperfine transition, as explained in our earlier work in Ref. [11]. However, the increased absorption level is smaller than what is seen in the buffer-gas filled cell. The transparency peak at line

![Image](367x698)

![Image](375x704)

![Image](403x698)

![Image](411x704)

![Image](403x643)

![Image](412x649)
center has a subnatural width of 5 MHz (0.8 Γ).

The experimental schematic for the CPT experiments, shown in Fig. 4, is the same as that for the EIT experiments, except that the probe and control beams are derived from the same laser. The control beam is locked to the $F = 1 \rightarrow F' = 1$ transition, while the probe beam is scanned around the same transition using a double-passed AOM. The shift of the AOM is compensated using another AOM, as shown in the figure. The scan width is 100 kHz after double passing. The beams are chosen to have circular polarizations (implemented using λ/4 wave plates), so that the selection rules will only allow the formation of a Λ-type three-level system when the magnetic sublevels for a $1 \rightarrow 1$ transition are used. As before, the cell (either pure or with 20 torr of Ne buffer gas) is placed inside a multilayer magnetic shield—the shielding is more important for CPT experiments because the resonances can split in the presence of a small magnetic field.

The results are shown in Fig. 5. As expected, CPT resonances are seen in both kinds of cells. The linewidth in both cases is less than 1 kHz, which is 1000 times smaller than the EIT resonance. More importantly, the resonance in a buffer-gas filled cell (480 Hz) is considerably smaller than the one obtained in a pure cell (750 Hz). This is the main reason that buffer-gas filled cells are used in applications of CPT like precise magnetometry and atomic clocks.

### III. CONCLUSIONS

Before summarizing the results presented, we consider the phenomenon of electromagnetically induced absorption (EIA). Just like two phase coherent beams can drive the atoms into a dark superposition state, one can use such beams to create a bright state. This leads to enhanced absorption in the system. In the first study of such a state using a closed $F \rightarrow F + 1$ transition in the $D_2$ line of $^{85}$Rb (with degenerate levels determined by $F \neq 0$), the authors found an enhancement by a factor of 1.7, and termed it electromagnetically induced absorption [14]. But it should more correctly called Coherent Population Trapping of a Bright State (CPTBS). The term EIA is more appropriate for phenomena where a weak phase-independent probe laser shows enhanced absorption when one (or more) strong control lasers are present. EIA is most commonly studied in 4-level N-type systems with two control lasers [15, 16]. However, we have recently shown that it can be observed in a degenerate two-level system, i.e. one where both control and
probe lasers are on the same transition \[17\]. In fact, both EIT and EIA can be studied in such two-level systems. And one can convert from EIT to EIA in a three-level Λ-type system by turning on a second control beam that is counter-propagating with respect to the first beam \[18\].

To conclude, we have highlighted the differences between the related phenomena of coherent population trapping, which requires two phase-coherent beams of roughly equal power, and electromagnetically induced transparency, which requires independent lasers with large power in the control beam and negligible power in the probe beam. The literature is full of cases where the term EIT is used for experiments that are of the CPT kind. Perhaps this is because of the pizazz associated with the phrase EIT. But an immediate clue as to the kind of experiment can be had from the number of lasers used: one laser implies CPT and two lasers implies EIT. \[19\] The two phase-coherent beams required for CPT are then produced by modulation, either acousto-optic or electro-optic. CPT experiments gain from the use of vapor cells filled with buffer gas, because this increases the ground-state coherence time and hence narrows the linewidth of the resonance. We show experimentally that EIT cannot be seen in such a cell. Under the right conditions, the control laser in EIT leads to subnatural resonances for probe absorption. We have recently shown that the use of a control beam with a Laguerre-Gaussian profile—instead of the usual Gaussian—leads to a further narrowing with an unprecedented linewidth of \[\Gamma/20\] being obtained \[20\].

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