

# Selective Processes between Coherent Population Trapping and Raman Adiabaticity via Electromanetically-Induced Transparency

ECE 695

Jungu Choi

Coherent population trapping (CPT) renders atoms in the ground states of a  $\Lambda$ -like system as shown in Figure 1 virtually irresponsive to excitation by photon. This phenomenon was predicted in the Schrödinger's equation where in the  $\Lambda$ -like system two resonances were treated independently while coherence between the two ground states was established [1]. The researchers noted that the excited state population dwindles with the strong presence of the coherence between the ground states. This led to the discovery of dark resonance which dates back to as early as 1970s when researchers found out in a three-level  $\Lambda$ -like system coherence in two photon transitions suppresses absorption of photons [2, 3].

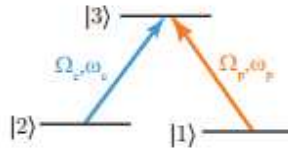


Figure 1. Coherent population trapping (CPT) occurs in the  $\Lambda$ -like system where two beams, coupling and probe beams, resonantly drive the transitions. Figure taken from Ref [11].

CPT prepares atoms in the superposition states, sometimes called dark states, via spontaneous decay and usually takes a long time to reach a steady state since it requires a few cycles of excitation and decay [5, 6]. Intuitively, it may take a very long time if the laser intensity is very small. The amplitude probability of the  $|1\rangle$  state dwindles and eventually vanishes in the steady state limit where the system has reached equilibrium. The final states can be expressed in the form as:

$$|D\rangle = \frac{\Omega_c|1\rangle - \Omega_p|2\rangle}{\sqrt{\Omega_p^2 + \Omega_c^2}}$$

Figure 2, from Ref [4], is the plot of the pure imaginary coherence term,  $\rho_{12}$ , which describes the excitation rate from the state  $|1\rangle$  to the state  $|3\rangle$ . This term depends highly on the population of the  $|1\rangle$  and  $|3\rangle$  states and therefore exhibits oscillatory behavior because the population of the ground states oscillate due to excitation and spontaneous decay. It can be seen that after a few cycles of spontaneous decay, the excitation rate shows smaller and smaller oscillation and eventually approaches zero (solid). When decoherence is introduced between the ground states, the excitation rate never approaches zero but does shows damped oscillatory behavior (dashed).

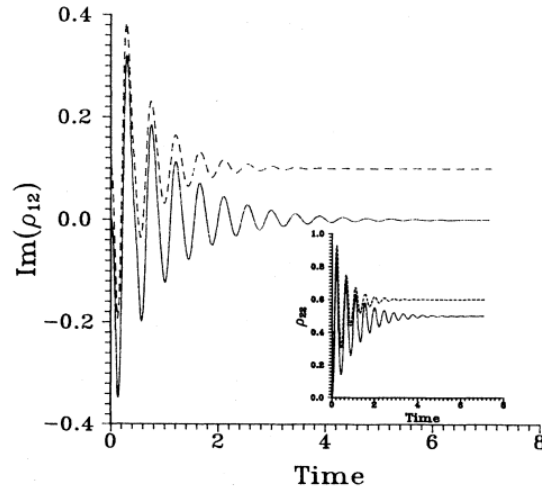


Figure 2. The pure imaginary coherence term,  $\rho_{12}$ , describing the excitation rate from the ground state to the excited state. The unit of time is a multiple of spontaneous decay time. See text for more. The inset shows the population of the ground state over time.

In the same structure, Raman spectroscopy prepares atoms in the Bloch sphere with two ground states ( $|1\rangle$  and  $|2\rangle$  in Figure 1) being the two levels. This process differs in that no direct excitation to the excited state ( $|3\rangle$  in Figure 1) occurs, which is due to the fact that the Raman lasers are far detuned from the resonant frequency. The Raman lasers are usually called, pump laser and Stoke laser (the equivalent of coupling and probe lasers in Figure 1). One of the schemes in Raman spectroscopy exploits adiabatic passage where either the intensity or the detuning of the laser slowly changes to effect complete population transfer from one ground state to the other [6]. Adiabaticity was observed in a multi-level system using a pico-second pulse (at 778.5 nm) with unity transfer efficiency in atomic Rubidium 87 [7]. This experiment exploits the frequency sweep of the pulse bandwidth of  $\sim 10$  nm to transfer atoms in the 5s state to the 5p state (at 780.2 nm) and then to the 5d state (at 775.9 nm).

Stimulated Raman Adiabatic Passage (STIRAP) uses adiabaticity by switching the Raman lasers on and off in a way that efficient population transfer from one ground state to the other (e.g. from  $|1\rangle$  to  $|2\rangle$  in Figure 1) may occur. Ye et al. observed adiabatic transfer of Rubidium gas in the ground states in a sub-nanosecond time frame [9]. With the Rabi frequency of the Raman lasers about ten times greater than the decay rate of the excited state, the authors showcased the STIRAP efficiency by collecting the absorption spectrum of the initial ground state. Normally, the laser pulses are generated in the Gaussian profiles and the falling edge of one Raman laser coincides with the rise of the other Raman laser. However, there are a few additional conditions that need to be satisfied for efficient population transfer via STIRAP [5, 10]. If these conditions are not met, adiabaticity fails and the lasers would excite atoms to the excited states, in which case, the process then becomes coherent population trapping with visible oscillation in the population [5]. In my previous paper, my advisor D. S. Elliott and I commented

on the works by Proite et al. [12], and Miles et al. [13] where the Wisconsin group observed unexpected low transfer efficiency in the STIRAP. Their experimental setup did not satisfy the STIRAP conditions laid down by Ref [10] and thus CPT prevailed in their sub-nanometer localization scheme [11].

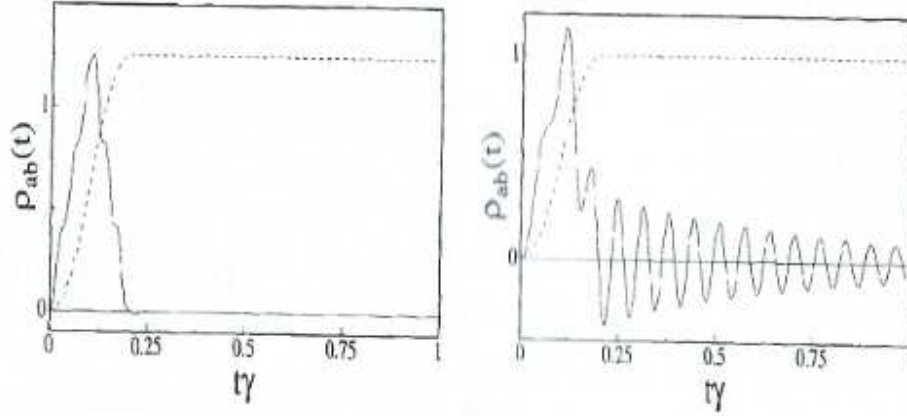


Figure 3. Successful STIRAP process (left) with population transfer within sub-nanoseconds and degradation of STIRAP into CPT due to unsatisfied conditions.

Even though successful STIRAP conditions depend heavily on the Rabi frequencies of the Raman lasers, there has been little research done concerning the degree of success in population transfer in the presence of multiple Zeeman sublevels.

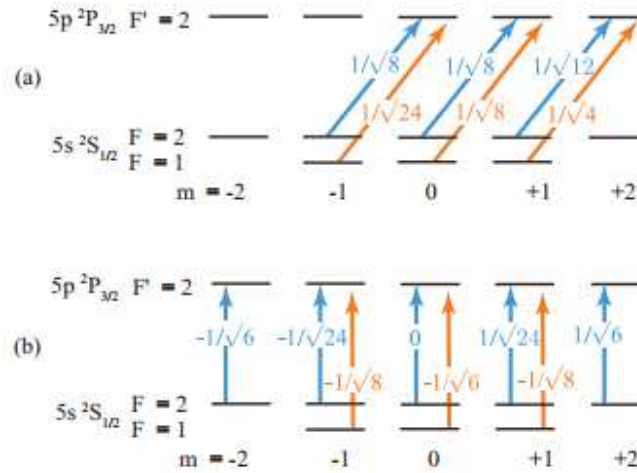


Figure 4. Clebsch-Gordon Coefficients for Rubidium D2 transitions with (a)  $\Delta m = +1$  by circularly polarized light and (b)  $\Delta m = 0$  by linearly polarized light. Figure from Ref [11].

Take for instance the Rubidium 87 system. In the circular polarization setup in Figure 4(a), the ratio of the two Rabi frequencies (blue and red) in  $m = -1$  level differs from that in  $m = +1$  by the

factor of 3. In the linear polarization setup in Figure 4(b), due to the presence of zero dipole moment in the  $m = 0$  level (blue), STIRAP cannot occur. Therefore, with certain laser intensity, STIRAP may occur in one Zeeman sublevel, while in others CPT occurs. If the hyperfine structures with multiple Zeeman sublevels are investigated closely, it is possible to excite atoms in a particular Zeeman sublevel while leaving atoms in the other Zeeman sublevels in the ground states. This is the idea of exciting atoms in a particular Zeeman sublevel via selective STIRAP and CPT.

- [1] E. Arimondo and G. Orriols, *Lett. Nuovo Cimento* 17, 333 (1976)
- [2] G. Alzetta, A. Gozzini, L. Moi, and G. Orriols, *Nuovo Cimento* 36B, 5 (1976).
- [3] H. R. Gray, R. M. Whitley, and C. R. Stroud, *Opt. Lett.* 3, 218 (1978).
- [4] I. V. Jyotsna and G. S. Agarwal, *Phys. Rev. A* 52, 3147 (1995).
- [5] M. O. Scully and M. S. Zubairy, *Quantum Optics* (Cambridge University Press, Cambridge 1997).
- [6] N. V. Vitanov, T. Halfmann, B. W. Shore, and K. Bergmann *Annu. Rev. Phys. Chem.* 2001. 52:763–809
- [7] B. Broers, H. B. van Linden van den Heuvell, and L. D. Noordam, *Phys. Rev. Lett.* 69, 2062 (1992).
- [8] Shao-Ying Meng, Li-Bin Fu and Jie Liu. *J. Phys. B: At. Mol. Opt. Phys.* 42 (2009) 185301.
- [9] C. Y. Ye, V. A. Sautenkov, Y. V. Rostovtsev, and M. O. Scully, *Opt. Lett.* 28, 2213 (2003).
- [10] J. R. Kuklinski, U. Gaubatz, F. T. Hioe, and K. Bergmann, *Phys. Rev. A* 40, 6741 (1989).
- [11] J. Choi and D. S. Elliott. *Phys. Rev. A* 89, 013414 (2014)
- [12] N. A. Proite, Z. J. Simmons, and D. D. Yavuz, *Phys. Rev. A* 83, 041803 (2011).
- [13] J. A. Miles, Z. J. Simmons, and D. D. Yavuz, *Phys. Rev. X* 3, 031014 (2013).