Indian J. Phys. **80** (5), 531-535 (2006)

IJP

A comparative study between Autler-Townes splitting and quenching of spontaneous emission

Tulika Tamuly and G D Baruah*
Department of Physics, Dibrugarh University, Dibrugarh-786 004, Assam, India

E-mail : gdbaruah@rediffmail.com

Abstract : Modification of spontaneous emission is an active research topic in quantum optics. The three-peak spectrum of resonance fluorescence was one of the first development in this area. Cavity electrodynamics has made possible the enhancement and suppression of spontaneous emission from an atom *via* a tailoring of the mode density. Eliminations of resonance fluorescence from a driven three-level atom was proposed in. Dynamical suppression has also been achieved from a driven, cavity-confined, two-level atom. Furthermore, it has been predicted and experimentally demonstrated that three level atoms can exhibit a narrowing of spectral linewidth on one transition controlled by coherent driving another transition. The coherent preparation of atomic state essential for this can be realized *via* Autler-Townes splitting. In the present work, we have worked out a correlation between Autler-Townes splitting and quenching of spontaneous emission *via* quantum interference. It is believed that the present correlation will be helpful in understanding the process of lasing without inversion.

Keywords : Autler-Townes splitting, quantum interference, lasing without inversion.

PACS Nos. : 42.55.Px, 42.50.-p, 42.50.Gy

1. Introduction

A number of discussions of various aspects about the theory of three-level lasers have appeared in the literature since Bloembergen [1] and others employed a semi classical approach to derive most of the theoretical properties of three-level systems. Of particular reference may be made about the statistical matrix method of Vuylsteke [2] who worked out the general equation of motion of the statistical matrix for a three-level system. In a three-level gas maser, Vuylesteke showed how splitting of emission line or the so-called *Autler-Townes* splitting occurs under certain conditions [3]. To understand how the splitting occurs, it is essential to consider a three-level system as was visualized by Bloembergen [1] where it is assumed that a strong radiation field is incident on the system which saturates the ground and the uppermost level. There is also a signal frequency which is relatively weak and this is incident on the upper two-levels. If the intensity of the radiation field coupling the saturated pair is increased beyond the minimum required to equalize the populations of the two levels, the perturbation of the levels becomes more and more effective until it becomes inappropriate to treat the radiation field as a perturbation. The field then has the effect of causing appreciable mixing of the two unperturbed states in times short relative to the transverse relaxation time $T2$. Under this conditions, transitions of the systems from or to a third-level are conditioned by the mixing of the states coupled by the pump field. The general effect of this is a splitting of the level at the signal-field frequency. Autler-Townes [3] splitting, and similar other phenomena like three-peak spectrum of *resonance fluorescence* [4–7], are considered as significant from the point of view of quenching of spontaneous emission *via* quantum interference. Modification of spontaneous emission is an active research topic in quantum optics [8]. It has been shown [9] that the emission spectrum can be substantially modified *via* atomic coherence and interference even for an atom in an ordinary

*Corresponding Author

vacuum. The coherent preparation of atomic states essentional for this effect can be realized *via Autler-Townes splitting* [10]. In a recent paper [11] it was shown that spectral line elimination and cancellation of spontaneous emission is possible under certain conditions, and experiment has also been performed to observe this phenomenon [12]. It was also shown [13] that the spectrum of resonance fluorescence under certain conditions can have spectral lines which are very narrow compared to the natural width of individual levels.

All spontaneous emission suppression effects mentioned above have one common origin the quantum interference of spontaneous transitions from two closely lying atomic levels to a third-level. The splitting of emission lines by mixing of the states coupled by the pumped field and quenching of spontaneous emission *via* quantum interference are presumably two different issues but still it is reasonable to believe that one effect influences the other. One of the interesting developments in quantum optics in recent years has to do with an idea involving atomic coherence and interference mediated by a strong electromagnetic field coupling two levels of an atom [1,3,14,15]. The phenomenon of electromagnetically induced suppression of absorption and lasing without inversion that has been much studied [16–20] and observed [21–23]. The fundamental physical principle here is quantum interference between the two routes by which an atom reaches the upper laser level through absorption of a photon. When the interference is destructive, the rate of absorption may be vanishingly small, whereas no such interference exists to make the rate of emission vanish. The semi classical theory of Scully and co-workers explain successfully all the basic physics of quantum interference and lasing without inversion. Its success stems from the fact that quantum interference originates from atomic coherence which is fully accounted for as long as the atom is treated quantum mechanically. In the sections to follow, are first considered the splitting of emission line under condition of strong E.M. field and also the cases of resonance modulation where under some circumstances, system becomes totally emissive or can be both emissive and dissipative.

2. System

The three-level system considered, is a Λ-type three-level atom with two closely lying lower level $|a\rangle$ and $|b\rangle$ and a single upper level $|c\rangle$ interacting with a strong field driving the lower two levels and with a weak probe field coupling each of the two levels to the upper level as shown in Figure 1. The frequency ω of the driving field is assumed to be in exact resonance with the atomic frequency $\omega_{ab} = (E_a - E_b)/\hbar$ and the frequency Ω of the probe field is considered to be sufficiently close to both the atomic frequencies area $= (E_c - E_a)/\hbar$ and $\omega_{cb} = (E_c - E_b)/\hbar$ that either of the upward transition $|a\rangle \rightarrow |c\rangle$ and $|b\rangle \rightarrow |c\rangle$ can occur with absorption of a probe photon. The driving field is assumed to be sufficiently strong and the probe field sufficiently weak that the lower doublet population are determined mainly by the driving field and that absorption of a probe photon can be treated by the 1st order perturbation theory.

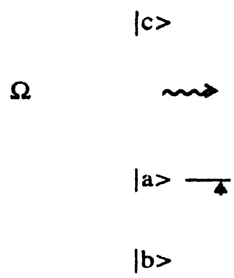

Figure 1. Three-level atom with levels of *c, a, b* in the presence of a strong field of frequency ω driving the lower two levels *a* and *b* and a weak probe field of frequency Ω coupling the two levels *a* and *b* to the upper level *c*.

It must be noted that this system is analogous to Bloembergen's original three-level systems where a strong field is incident between lower-two level and a weak field is incident between upper and lower level. However in a Bloembergens systems, the topic of quantum interference is not discussed but we shall see in the following sections that a system may behave as quantum system the system, may be emissive and as well as absorptive or dissipative under some circumstances. This is analogous to quantum interference.

3. Splitting of emission line and the equation of motion of statistical matrix

We consider a μ-system with an unperturbed energy level scheme consisting of three non-degenerate levels two of these form a closely spaced doubbt far removed from the third-level and it is assumed that the transition matrix element exist in zero order between the two components of doublet as well as between the third level and one of the doublet level.

Suppose the Stark electric field which is applied to the μ-system to be constant in time. Then since we have assumed a vanishing 1st order effect and since the second order perturbation of any level depends inversely on the energy separation between that level and the other levels in the level diagram, we may expect that for field strengths which result in appreciable perturbation of the doublet the third relatively isolated, level will not be changed appreciably by the field. This result is illustrated in Figure 2. Depending upon the particular situation, and the strength of the perturbing field, a number of changes in the absorption spectrum may be expected. In general, in the unperturbed spectrum, the two absorption lines have control frequencies υ_{32}^{1} and υ_{21}^{0}, these lines will appear at slightly different frequencies $\upsilon_{21}^{1} < \upsilon_{32}^{0}$ and $\upsilon_{21}^{1} > \upsilon_{21}^{0}$. In addition, because of the mixing of the doublet levels by the Stark field, a third line, at frequencies υ_{31}^{1} corresponding to a forbidden transition in the unperturbed spectrum may become apparent in the perturbed spectrum.

The splitting of the spectral line is manifested by the formula [24] :

$$\frac{1}{Q_{MS}} \quad \frac{1}{Q_{MO}} : \frac{\left[1-(3\in -1)S^2\right]\left(1+S^2-F^2\right)+2F^2\left[1-2(\in -1)S^2\right]}{\left(1+4S^2\right)\left[\left(1+S^2-F^2\right)^2+4F^2\right]} \tag{1}$$

$$Q_{MS}' \equiv Q_{MS}\frac{1-2(\in -1)S^2}{\left(1+S^2-F^2\right)+4S^2}\ ;\ \in=\frac{\upsilon_{21}}{\upsilon_{32}}. \tag{2}$$

The general behaviour of $1/Q_{MS}$ is displayed in Figure 2(a) in which the quantity $(-Q_{MO}/Q_{MS})$ with $\in = 0$, 3 has been plotted as a function of F for several values of parameter S^2. The material can be both emissive and dissipative within the same line as indicated by the curve for $S^2 = 1$.

Finally, the feature of major interest is the resonance modulation splitting which is displayed both for a totally dissipative line ($S^2 = 1/8$) and for the emissive lines ($S^2 = 3$, $S^2 = 1$) and both dissipative and emissive lines ($S^2 = 1/9$).

The material can be both emissive and dissipative within the same line as indicated by the curve for S^2=1, and the resonance modulation splitting which is displayed both for a totally dissipative line ($S^2 = 1/8$) and for the emissive line ($S^2 = 3$, $S^2 = 5$).

For $S^2 >>1$, eq. (1) reduces to

$$Q_{MS} - \frac{(3\in -1)}{4Q_{MO}}\frac{S^2-\left(\frac{2\in}{3\in -1}\right)F^2}{\left(S^2-F^2\right)+4F^2} \tag{3}$$

From eq. (3) when we put $\in = 0$, we get expression $1/Q_{MS}$ as

$$\frac{1}{Q_{MS}} \quad \frac{1}{Q_{MO}\ (S^2-F^2)^2+4F^2}$$

$$\frac{Q_{MO}}{QMS} = \frac{S^2}{(S^2-F^2)^2+4F^2}.$$

On plotting L.H.S. *vs.* F, we get the graphs as shown in Figures 2(a,b,c). Here, $1/Q_{MS}$ has the maximum value at $F^2 = 0$ *i.e.* $\delta_S^2\tau^2 = 0$.

4. Quenching of spontaneous emission and spectral line elimination :

We consider a three-level model atom as shown in

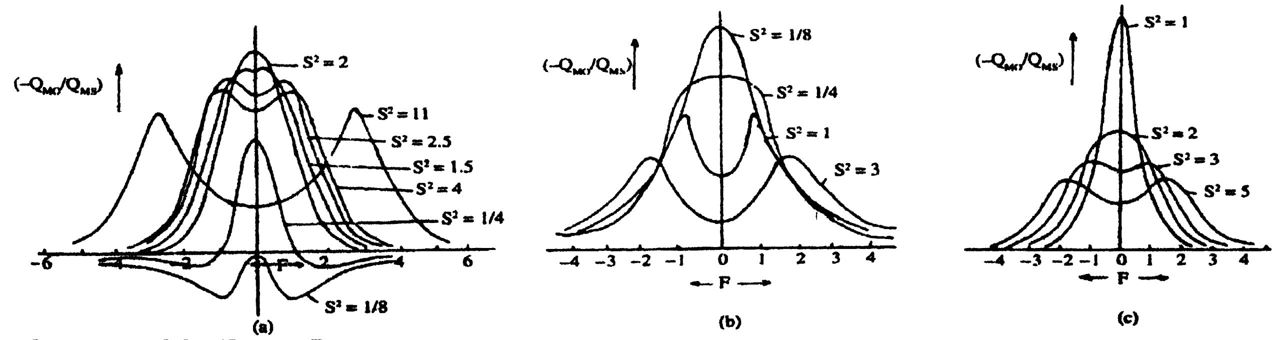

Figure 2. The plot of Q_{MO}/Q_{MS} *vs.* F.

Figure 3. It has two upper levels $|a_1>$ and $|a_2>$ which are coupled by the same vacuum modes to the lower level $|c>$. The two upper levels are coupled by strong coherent field with frequency υ_0 to another upper lying level $|b>$. The interaction picture Hamiltonian can be written as

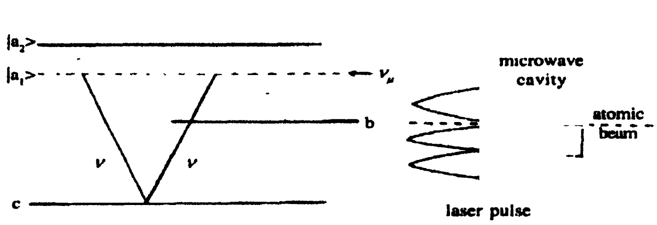

Figure 3. Scheme of emission cancellation into a single mode.

$$\upsilon = \hbar\Omega_1 e^{i\Delta_1 t} |a_1><b| + \hbar\Omega_2 e^{i\Delta_2 t} |a_2><b| + H.C.$$
$$+\sum g_k^1 e^{i(w/c-v_k)t} |a_1 >< c|b_k$$
$$+g_k^{(2)} e^{i(w/c-vk)t}|a_2><c|b_k + H.C. \quad (4)$$

Now, in steady state, the probability amplitude $C_k(\alpha)$ of the atom being in the lower level with one photon emitted, is given by [25–27]

$$C_K(\alpha) = \sum_{j=1}^{3} \frac{i(g_k^{(1)}\alpha_j + g_k^{(2)}\beta_j)}{-\lambda_j + i[\upsilon_k - (\omega_{bc} + \upsilon_0)]}. \quad (5)$$

Since the spontaneous emission spectrum is proportional to $|C_k(t = \alpha)|^2$ one might expect that there would be three peaks in the spectrum corresponding to the three resonant denominators in eq. (5).

5. Comparison of the results of Aulter-Townes splitting and quenching of spontaneous emission

It is appropriate now to summarize the results as indicated in the earlier sections and make a comparison between the two schemes which have been our main aim in the present work. The salient points of the quenching of the spontaneous emission was in the following facts and it is essential to discuss the points for our convinience. It is clear that the nature of the quenching including the spectral narrowing and splitting should also determines their curve. This situation is definely connected with the historical development of the three-ievel maser idea given originally by Bloembergen. As indicated in Figure 3, if microwave radiation appropriately mixes two upper states, then emission (both spontaneous and stimulated) of photon with frequency ν is cancelled. As shown in eq. (1), there would be splitting of emission lines and three peaks would be observed corresponding to three resonant denominators for $\rho = 0$. However for $\rho = 1$, we can have only two peaks. A simple explanation of peak elimination can also be given the dressed state picture as shown by eq. (5). In all the cases, we observe that the principle of superposition and mixing of states is applicable; under these circumstances, *quenching of elimination* does occur. But we have observed that though in Aulter-Towne's splitting, superposition of states is not considered, splitting and quenching do occur. In a recent work [28], it was shown that Aulter-Towne's spectrum quenching and splitting of spectral line occur simultaneously and maximum quantum interference achieved is a V-type atoms coupled to a single mode. If this is so, Aulter-Towne's splitting plays a significant role in quenching of spontaneous emission.

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