Effect of the continuum on electromagnetically induced transparency with matched pulses

S. J. van Enk,[1,2] Jian Zhang,[2] and P. Lambropoulos[1,2]
[1]*Foundation for Research and Technology—Hellas, Institute of Electronic Structure and Laser, P.O. Box 1527, Heraklion 71110, Crete, Greece and Department of Physics, University of Crete, Crete, Greece*
[2]*Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, D-85748 Garching, Germany*

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We discuss how transparency and population trapping effects are affected when a realistic continuum is involved. We consider the propagation of matched pulses in a Λ-like system, where the upper level is replaced by a continuum.

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A laser field coupling two of the three levels in a Λ scheme can make an atomic medium transparent to probe radiation that is resonant with the other transition. Such an effect is called electromagnetically induced transparence (EIT), and this type of EIT was first demonstrated experimentally [1], and has later been further investigated theoretically [2,3]. Recently Harris [3] proved that under the right initial conditions for the applied coupling and probe fields, the medium will be driven towards a trapped state that is transparent to a certain superposition of these two propagating fields; since this very superposition is the field *produced* by the medium in this trapped state, both transparency and trapping will continue to exist, also in time-dependent pulses. The suggestion has been made that these effects persist when the upper state is replaced by a continuum [1–3]. Here we will show, however, that under the same pulsed conditions the effect of atoms and fields producing transparency and trapping at the same time does not exist for a realistic continuum. More precisely, only if the continuum is modeled in such a way that the asymmetry parameter q, to be defined below, is zero, does this effect remain [4].

On the other hand, we have already shown elsewhere that a transparency will develop *inherently* for an autoionizing state [5]. That is, a probe field can induce its own transparency without need for an additional coupling laser. The required destructive interference in the absorption is now supplied by the configuration interaction with the continuum, which provides a second (indirect) channel for ionization. There we also showed that the effect is quite robust: deviations from ideal conditions lead only to small atomic decay and small photon absorption. The same is shown to be true here. Although strictly speaking the transparency and the steady state are not reached in a time-dependent field, the absorption of a probe field can nevertheless be dramatically decreased, also through coupling to the continuum.

When one replaces the discrete upper level in a Λ scheme by a continuum, one in fact describes the so-called laser-induced continuum structure (LICS). The coupling laser induces a pseudoresonance structure in the continuum which will be probed by the probe laser field. For a review on LICS see [6]. We describe the probe and coupling fields by the amplitudes a_p and a_c, respectively, which are normalized such that their modulus squared gives the number of photons per atom. The coupling of the two bound states e and g to the continuum and to nonresonant bound states results in an effective shift of the energy levels (ac Stark shift) and in a broadening. The broadening arises from the pole part of the coupling to the continuum. For simplicity the shifts will be neglected hereafter. The effective field-dependent decay rates from the two bound states to the continuum are given by the respective dipole coupling matrix elements squared, and will be written here as

$$\Gamma_g=\Gamma_{g0}|a_p|^2 ,\qquad \Gamma_e=\Gamma_{e0}|a_c|^2 . \tag{1}$$

The constants Γ_{e0} and Γ_{g0} have the physical meaning of the respective decay rates in the presence of one photon per atom. Conversely, they are also equal to the respective photon absorption rates in the presence of one atom per photon.

Using a standard derivation one finds the slowly varying atomic amplitude equations for the two bound states,

$$\frac{\partial}{\partial t}c_g=-\tfrac{1}{2}\Gamma_g c_g-i\Omega(q-i)c_e ,\qquad \frac{\partial}{\partial t}c_e=-\tfrac{1}{2}\Gamma_e c_e-i\Omega^*(q-i)c_g+i\delta c_e . \tag{2}$$

Formally q is defined as the ratio of the principal value part plus the bound part of the two-photon dipole matrix elements to the pole contribution of the continuum [6,7]. Physically it represents the relative magnitude of the coupling of the two discrete states compared to the product of decays directly into the continuum. We note that for $q=0$ the equations are equivalent to those for a discrete Λ system, when the upper state has been adiabatically eliminated, as in [2,3]. We will show that a nonzero q prohibits the occurrence of above-mentioned effects. The quantity Ω, defined here as

$$\Omega=\tfrac{1}{2}\sqrt{\Gamma_{e0}\Gamma_{g0}}a_p^* a_c , \tag{3}$$

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is useful in that it underscores the symmetry between the equations (2) for the atomic amplitudes and (6) for the field amplitudes. It is worth noting that for a system involving a continuum such that $q=0, \Omega$ is identical to the two-photon Rabi frequency coupling the two lower states of the Λ system. Finally, the detuning of the probe field with respect to the coupling laser is defined as $\delta=\omega_p+E_g-(\omega_c+E_e)$.

The equations for the field amplitudes can be cast into a similar form as the atomic equations when one recognizes the correspondence relations

$$c_g \leftrightarrow a_p ; \quad c_e \leftrightarrow a_c .$$

To make this explicit, we introduce the photon absorption rates

$$\begin{aligned} \Gamma_p &= \Gamma_{g0}|c_g|^2 , \\ \Gamma_c &= \Gamma_{e0}|c_e|^2 , \end{aligned} \tag{4}$$

and the coherent photon exchange rate

$$\tilde{\Omega}=\tfrac{1}{2}\sqrt{\Gamma_{e0}\Gamma_{g0}}c_g^* c_e . \tag{5}$$

One finds then

$$\begin{aligned} \frac{d}{dt}a_p &= -\tfrac{1}{2}\Gamma_p a_p - i\tilde{\Omega}(q-i)a_c , \\ \frac{d}{dt}a_c &= -\tfrac{1}{2}\Gamma_c a_c - i\tilde{\Omega}^*(q-i)a_p , \end{aligned} \tag{6}$$

where $d/dt=\partial/\partial t+c\partial/\partial z$, assuming one-dimensional propagation in the z direction at the same speed c for both fields (this is the same assumption as used by Harris [2,3]). Thus, apart from the detuning δ occurring in the atomic equations, the analogy between field and atoms is manifest. Using this format, then, it is easy to derive the two conservation laws

$$\begin{aligned} \frac{\partial}{\partial t}|c_g|^2 &= \frac{d}{dt}|a_p|^2 , \\ \frac{\partial}{\partial t}|c_e|^2 &= \frac{d}{dt}|a_c|^2 , \end{aligned} \tag{7}$$

expressing the fact that on each absorption of a probe (coupling) photon one atom is removed from the ground (excited) state. Furthermore, the total ionization rate, equal to the total photon absorption rate, is given by

$$\frac{\partial}{\partial t}(|c_g|^2+|c_e|^2)=\frac{d}{dt}(|a_p|^2+|a_c|^2)=-|R|^2 \tag{8}$$

with

$$R=\sqrt{\Gamma_{e0}}a_c c_e+\sqrt{\Gamma_{g0}}a_p c_g . \tag{9}$$

Now consider the rate of change of R due to the atomic evolution only. One finds

$$\left[\frac{\partial R}{\partial t}\right]_{\text{atom}} = -\tfrac{1}{2}(\Gamma_e+\Gamma_g+iq\Gamma_e)R - i(\tfrac{1}{2}q[\Gamma_g-\Gamma_e]-\delta)\sqrt{\Gamma_e 0}a_c c_e , \tag{10}$$

which shows that a stable atomic state will be reached in *constant* fields if the detuning satisfies

$$\delta=\tfrac{1}{2}q(\Gamma_g-\Gamma_e) , \tag{11}$$

a relation which has been derived before [8]. The condition (11), however, cannot be satisfied at all times in a pulsed field. The only thing one can hope for is to come close to (11) during the major part of the pulse. Similarly, the rate of change of R due to the fields is

$$\left[\frac{dR}{dt}\right]_{\text{field}} = -\tfrac{1}{2}(\Gamma_c+\Gamma_p+iq\Gamma_c)R - \tfrac{1}{2}iq(\Gamma_p-\Gamma_c)\sqrt{\Gamma_{e0}}c_e a_c . \tag{12}$$

Hence, this leads to an *additional* condition $\Gamma_c=\Gamma_p$ for transparency that, again, cannot be satisfied in general (when $q\neq 0$) at all times in a time-varying field. On the other hand, this condition will be satisfied, as we will show below, if the initial applied coupling and probe field contain the same number of photons, i.e., $|a_c|^2=|a_p|^2$.

When $q=\delta=0$, the quantity R will always be driven to zero, both in space and in time, irrespective of initial conditions. A discrete system will, therefore, at zero detuning be driven towards a steady state without decay and without photon absorption. We note here that δ is indeed implicitly taken to be zero in [3], and also in related work [9].

For a discrete Λ system it is easy to define a quantity linear in the atomic amplitudes that is conserved in *constant* fields. The unique (up to a scale factor) solution which is linear in field amplitudes as well, is

$$Q=\sqrt{\Gamma_{g0}}a_p^* c_e-\sqrt{\Gamma_{e0}}a_c^* c_g . \tag{13}$$

It is not possible, however, to define a conserved quantity when $q\neq 0$. A similar quantity is found to be convenient in [9], but there it is not proven that this quantity will reach a steady-state value. Furthermore, in their numerical example the condition $\Gamma_{e0}=\Gamma_{g0}$ was chosen, which implies that Q is accidently always conserved. Namely, the rate of change of Q due to the evolution of the atomic variables is

$$\left[\frac{\partial Q}{\partial t}\right]_{\text{atom}} = \tfrac{1}{2}iq\Gamma_g Q+i(\delta-\tfrac{1}{2}q[\Gamma_g-\Gamma_e])\sqrt{\Gamma_{g0}}a_p^* c_e , \tag{14}$$

while the change of Q due to the fields is

$$\left[\frac{dQ}{dt}\right]_{\text{field}} = (\Gamma_{e0}-\Gamma_{g0})R^* c_g c_e + \tfrac{1}{2}iq\sqrt{\Gamma_{e0}\Gamma_{g0}}c_e c_g \times(\sqrt{\Gamma_{g0}}a_c^* c_e^* - \sqrt{\Gamma_{e0}}a_p^* c_g^*) . \tag{15}$$

This shows that, when $q=\delta=0$, this variable will reach a steady-state value both in time and in space, since R will be driven to zero. When $q\neq 0$ one again needs the condition (11), and even then $|Q|$ is conserved only in constant fields.

We can now reconstruct the concept of normal modes in a discrete Λ system as defined in [3], which shows at the same time how the two approaches of Refs. [3] and [9] are connected. At any given position one can find

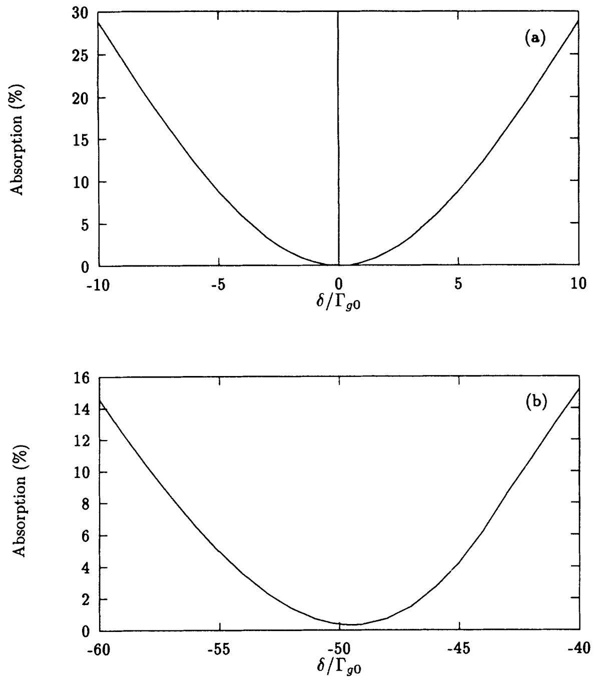

FIG. 1. (a) Relative absorption of probe field after propagating over a time $\Delta t = 10\Gamma_{g0}^{-1}$ as a function of detuning δ for a discrete Λ system (i.e., $q=0$). Photon absorption coefficients are $\Gamma_{e0}=\Gamma_{g0}$, the pulses are Gaussian with intensity given by $I \propto \exp[-(t/\tau)^2]$ with $\tau = 2(\Gamma_{g0})^{-1}$, and the initial peak values of the number of photons per atom are $|a_p|^2=1$ and $|a_c|^2=100$. (b) Same as (a), but with upper level replaced by a continuum with $q=1$. The optimum detuning is found to be $\delta=-49.5\Gamma_{g0}$, where the absorption is 0.33%.

coefficients λ_1 and λ_2 such that

$$b_1 \equiv \lambda_1 \sqrt{\Gamma_{e0}} c_e + \lambda_2 \sqrt{\Gamma_{g0}} c_g = 0 \ .$$

Then, substituting this relation into the definition of R, shows that the linear combination of field amplitudes

$$s \equiv \lambda_1 a_p - \lambda_2 a_c$$

will be driven to zero, while at the same time the two linear combinations

$$h \equiv \Gamma_{g0} \lambda_2 a_p^* + \Gamma_{e0} \lambda_1 a_c^*$$

and

$$b_2 \equiv \sqrt{\Gamma_{g0}} \lambda_2^* c_e - \lambda_1^* \sqrt{\Gamma_{e0}} c_g \ ,$$

corresponding to Q, will reach a (nonzero) steady-state value [10]. It is straightforward to show that the reverse is true as well: if, e.g., $h=0$, then b_2 will be driven to zero and the pair (s,b_1) will reach a steady state. Conversely, if one applies coupling and probe fields with the same temporal envelopes (matched pulses [3]), the ratio between the field amplitudes is fixed, and will remain fixed. This ratio determines the value of λ_1/λ_2 and thereby at the same time the steady atomic state. In the special case that $|\lambda_1| = |\lambda_2|$, the populations will be driven towards a steady state in which the photon absorption rates are equal, $\Gamma_c = \Gamma_p$. Thus, the normal modes (s,b_1) and (h,b_2), as found in Ref. [3], can be constructed from the quantity Q, as used in Ref. [9], and R.

We now take a numerical example similar to the one used in Ref. [3], to study the influence of a nonzero q value (see Fig. 1). We take the photon flux of the coupling field, $|a_c|^2$, 100 times as large as that of the probe field, $|a_p^2|$, and take equal absorption coefficients $\Gamma_{e0}=\Gamma_{g0}$. We plot the relative peak intensity of the probe pulse after it has propagated over a distance where, without coupling field, this value would have decayed to the value $\exp(-10) \approx 4.5 \times 10^{-5}$. When $q=0$ [Fig. 1(a)] there is no loss at the peak at zero detuning, while at not too large detuning the loss is still much smaller than without the coupling laser. For $q=1$ [Fig. 1(b)], there is a great loss at zero detuning, and the coupling laser has no positive effect. Instead, one finds almost lossless propagation at large negative detuning around $\delta \approx -50\Gamma_{g0}$, which is nothing but an effective time-averaged condition (11). The total peak loss is then 0.33%. The fact that this loss is still very small is partly due to the assumption that the two applied laser pulses are and remain completely overlapping. Indeed, related to this, it has been shown recently [11] that for the same system population transfer through the continuum is inhibited more seriously compared to that in a discrete Λ system, since this transfer is in general larger when a delay is introduced between the two pulses. For the optimum population transfer the same condition (11) would be needed, but with delayed pulses it is no longer possible to fulfill this requirement, even not approximately.

Let us finally remark that we did not include the extra decay from the excited state due to the probe field, and from the ground state due to multiphoton transitions in the coupling laser field [7]. One of these decays may be small, under special conditions both of them might be small, but in general they always diminish the coherent effect of transparency. Furthermore, the ac Stark shifts, which may be small too, affect the detuning in a time-dependent way, but do not necessarily interfere destructively, partly because this shift has the same time dependence as the atomic decay rates, partly because these shifts may in principle be compensated for by chirping the laser frequencies [12].

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