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Effect of DC field coupling on the photoelectron spectrum from double auto-ionising levels

W Leoński, R Tanaś and S Kielich

Nonlinear Optics Division, Institute of Physics, A Mickiewicz University, 60-780 Poznań, Poland

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Abstract. A system containing two auto-ionising levels diluted in two orthogonal continua and mutually coupled by a DC electric field is discussed. The long-time photoelectron spectrum from such a system is calculated for arbitrary values of the DC and laser fields. In addition, the quasi-energies of the 'dressed' states are calculated. The effects of the DC field coupling and the finite auto-ionising width of the second level on the spectrum are discussed and illustrated graphically. The effects of the 'confluence of coherences' and of 'population trapping' are also investigated.

We discuss the atomic model shown in figure 1, which is the same as that discussed by Agarwal *et al* (1986) and by Leoński *et al* (1988). The ground state $|0\rangle$ is coupled to the continuum $|c_1\rangle$ and the auto-ionising level $|1\rangle$ by an external laser field of frequency ω_L; in addition, the level $|1\rangle$ is coupled to the continuum $|c_1\rangle$ and the second auto-ionising level $|2\rangle$. The two auto-ionising levels lie close together and are mutually coupled by the DC electric field. The state $|2\rangle$ is diluted in the second continuum $|c_2\rangle$. Owing to the different parities of the continua $|c_1\rangle$ and $|c_2\rangle$, there is no coupling between the ground state $|0\rangle$ and the continuum $|c_2\rangle$. Moreover, we neglect all threshold effects and continuum–continuum transitions. However, we do not make any assumptions concerning the strengths of the external fields. Using $h/2\pi = 1$ units, we may write the following Hamiltonian describing our system:

$$H = (E_0 + \omega_L)|0\rangle\langle 0| + E_1|1\rangle\langle 1| + E_2|2\rangle\langle 2| + \int d\omega_1\, \omega_1|\omega_1\rangle\langle\omega_1| + \int d\omega_2\, \omega_2|\omega_2\rangle\langle\omega_2| + \Big(|1\rangle V_{12}\langle 2| + |0\rangle\Omega_{01}\langle 1| + \int d\omega_1\, |0\rangle\Omega_0(\omega_1)\langle\omega_1| + \int d\omega_1\, |1\rangle V_1(\omega_1)\langle\omega_1| + \int d\omega_2\, |2\rangle V_2(\omega_2)\langle\omega_2| + \text{HC}\Big). \qquad (1)$$

We also assume that all couplings by the external fields are of the electric dipole type only. We do not use Fano diagonalisation (Fano 1961). Applying standard procedures (Rzazewski and Eberly 1981), we write the equations of motion for our atomic system:

$$i\frac{da}{dt} = b_1\Omega_{01} + \int d\omega\, c_1(\omega)\Omega_0(\omega) \qquad (2a)$$

$$i\frac{db_1}{dt} = b_1\delta_1 + a\Omega_{01} + b_2V_{12} + \int d\omega\, c_1(\omega)V_1(\omega) \qquad (2b)$$

$$i\frac{db_2}{dt} = b_2\delta_2 + b_1V_{12} + \int d\omega\, c_2(\omega)V_2(\omega) \qquad (2c)$$

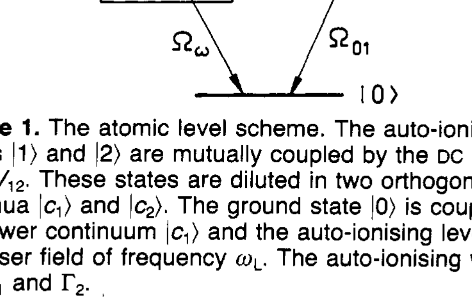

Figure 1. The atomic level scheme. The auto-ionising states $|1\rangle$ and $|2\rangle$ are mutually coupled by the DC electric field V_{12}. These states are diluted in two orthogonal continua $|c_1\rangle$ and $|c_2\rangle$. The ground state $|0\rangle$ is coupled to the lower continuum $|c_1\rangle$ and the auto-ionising level $|1\rangle$ by the laser field of frequency ω_L. The auto-ionising widths are Γ_1 and Γ_2.

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$$i\frac{dc_1(\omega)}{dt} = \Delta c_1(\omega) + a\Omega_0(\omega) + b_1V_1(\omega) \qquad (2d)$$

$$i\frac{dc_2(\omega)}{dt} = \Delta c_2(\omega) + b_2V_2(\omega) \qquad (2e)$$

where $a(t)$, $b_i(t)$ and $c_i(t)$ ($i = 1, 2$) are the probability amplitudes for the states $|0\rangle$, $|i\rangle$ and $|c_i\rangle$ ($i = 1, 2$) respectively. Moreover, we have introduced the detunings $\Delta = \omega - E_0 - \omega_L$ and $\delta_{1,2} = E_{1,2} - E_0 - \omega_L$, using the energies for the states specified above. We assume that all matrix elements are real and are flat functions of the continuum energy ω. It is highly convenient to transform equations (2) using the Laplace transform method. Therefore, applying the 'pole approximation' (Lambropoulos and Zoller 1981), we may write the following equations for the Laplace transforms:

$$(z + \Gamma_0)a(z) + (i\Omega_{01} + \Gamma_{01})b_1(z) = 1 \qquad (3a)$$

$$(i\Omega_{01} + \Gamma_{01})a(z) + (z + i\delta_1 + \Gamma_1)b_1(z) + iV_{12}b_2(z) = 0 \qquad (3b)$$

$$iV_{12}b_1(z) + (z + i\delta_2 + \Gamma_2)b_2(z) = 0 \qquad (3c)$$

where $a(z)$, $b_1(z)$ and $b_2(z)$ are the transforms of the amplitudes $a(t)$, $b_1(t)$ and $b_2(t)$ respectively. We have assumed here that at $t = 0$ the system was in the state $|0\rangle$. Moreover, we have introduced in (3) the following widths:

$$\begin{aligned}\Gamma_0 &= \pi\Omega_0^2(\omega)\\ \Gamma_{1,2} &= \pi V_{1,2}^2(\omega)\\ \Gamma_{01} &= \pi\Omega_0(\omega)V_1(\omega).\end{aligned} \qquad (4)$$

The set of equations (3) can be solved and the solutions have the following form:

$$\begin{aligned}a(z) &= \frac{(z + i\delta_1 + \Gamma_1)(z + i\delta_2 + \Gamma_2) + V_{12}^2}{D(z)}\\ b_1(z) &= -\frac{(i\Omega_{01} + \Gamma_{01})(z + i\delta_2 + \Gamma_2)}{D(z)}\\ b_2(z) &= \frac{iV_{12}(i\Omega_{01} + \Gamma_{01})}{D(z)}\end{aligned} \qquad (5)$$

where

$$D(z) = (z + \Gamma_0)[(z + i\delta_1 + \Gamma_1)(z + i\delta_2 + \Gamma_2) + V_{12}^2] - (i\Omega_{01} + \Gamma_{01})^2(z + i\delta_2 + \Gamma_2). \qquad (6)$$

Obviously the denominator $D(z)$ appearing in equations (5) is a third-order polynomial in z. The roots of $D(z)$ are the complex quasi-energies for the atomic states 'dressed' by the external fields. Although it is possible to find the exact analytical expressions for the zeros, we will restrict our considerations to two cases: (i) that of a weak laser field and (ii) that of a weak DC electric field. For weak laser fields ($\Gamma_0 \ll V_{12}$) the zeros of $D(z)$ are given by

$$\begin{aligned}z_1 &= 0\\ z_{2,3} &= -\tfrac{1}{2}[\Gamma_1 + \Gamma_2 + i(\delta_1 + \delta_2)]\\ &\quad \pm \tfrac{1}{2}\{[\Gamma_1 + \Gamma_2 + i(\delta_1 + \delta_2)]^2\\ &\quad - 4[V_{12}^2 + (\Gamma_1 + i\delta_1)(\Gamma_2 + i\delta_2)]\}^{1/2}.\end{aligned} \qquad (7)$$

For weak DC fields ($V_{12} \ll \Gamma_0$) the zeros occur for

$$\begin{aligned}z_1 &= -i\delta_2 - \Gamma_2\\ z_{2,3} &= -\tfrac{1}{2}(\Gamma_0 + \Gamma_1 + i\delta_1) \pm \tfrac{1}{2}\{(\Gamma_0 + \Gamma_1 + i\delta_1)^2\\ &\quad - 4[\Gamma_0(\Gamma_1 + i\delta_1) - \Gamma_{01}^2(1 + iq)]\}^{1/2}\end{aligned} \qquad (8)$$

where we have introduced the Fano asymmetry parameter q (Fano 1961). According to equations (2d) and (2e), we have the following relations for the Laplace transforms $c_1(\omega; z)$ and $c_2(\omega; z)$ of the continua amplitudes:

$$\begin{aligned}c_1(\omega; z) &= -\frac{i}{z + i\Delta}(a(z)\Omega_0(\omega) + b_1(z)V_1(\omega))\\ c_2(\omega; z) &= -\frac{i}{z + i\Delta}b_2(z)V_2(\omega).\end{aligned} \qquad (9)$$

We can now define the long-time photoelectron spectrum $W(\omega)$ using the complex amplitudes $c_1(t)$, $c_2(t)$ or their Laplace transforms. Since the continua are orthogonal, $W(\omega)$ has the form of the simple sum of the spectra for transitions to the two continua:

$$\begin{aligned}W(\omega) &= \lim_{t\to\infty}(|c_1(\omega; z)|^2 + |c_2(\omega; z)|^2)\\ &= [|(z + i\Delta)c_1(\omega; z)|^2 + |(z + i\Delta)c_2(\omega; z)|^2]_{z=-i\Delta}.\end{aligned} \qquad (10)$$

Using the solutions for the transforms $a(z)$, $b_i(z)$ and $c_i(\omega; z)$ ($i = 1, 2$), we obtain the formula for the photoelectron spectrum as

$$\pi W(\omega) = \Gamma_0\, N(\omega)/M(\omega) \qquad (11)$$

where

$$\begin{aligned}N(\omega) &= |(\Delta_2 + i\Gamma_2)(\Delta_1 + q\Gamma_1) - V_{12}^2|^2\\ &\quad + \Gamma_1\Gamma_2|V_{12}(q - i)|^2\\ M(\omega) &= |(\Delta_2 + i\Gamma_2)[(\Delta + \Gamma_0)(\Delta_1 + i\Gamma_1)\\ &\quad - \Gamma_0\Gamma_1(q - i)^2] - V_{12}^2(\Delta + i\Gamma_0)|^2\end{aligned} \qquad (12)$$

and

$$\begin{aligned}\Delta_{1,2} &= \Delta - \delta_{1,2} = \omega - E_{1,2}\\ q &= \Omega_{01}/\Gamma_{01}.\end{aligned} \qquad (13)$$

The spectrum given by the above formulae is valid for any strength of the laser and DC fields. This spectrum is presented in figure 2 for the case of weak DC coupling ($V_{12} = 0.3$). The laser field is assumed to be strong ($\Omega = 3$). We define the Rabi frequency Ω in the same way as Rzazewski and Eberly (1981, 1983). We have also assumed that $q = 100$, $E_1 = E_0 + \omega_L = 1$ and

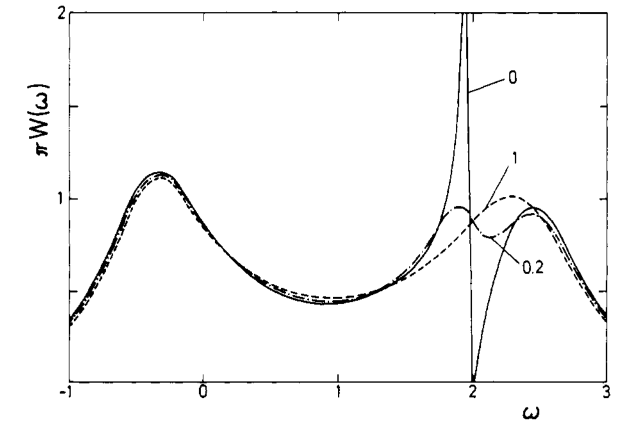

Figure 2. Photoelectron spectrum for a strong laser field ($\Omega = 3$) and various values of the auto-ionising width Γ_2. The DC electric field is weak ($V_{12} = 0.3$). The asymmetry parameter $q = 100$, $E_1 = E_0 + \omega_L = 1$ and $E_2 = 2$. All energies are in units of Γ_1.

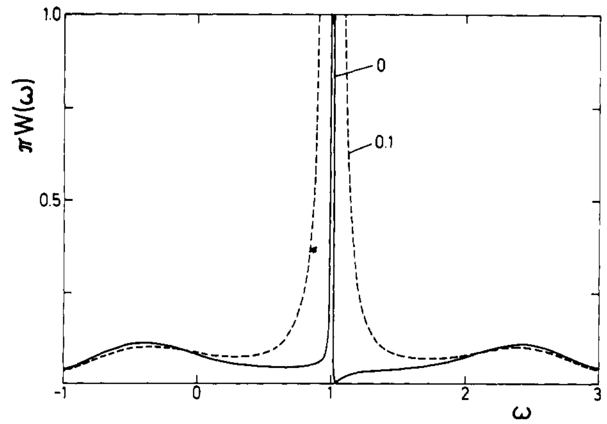

Figure 3. Photoelectron spectrum for a weak laser field ($\Omega = 1$) and various values of Γ_2. The DC field coupling $V_{12} = 1.5$ and $E_2 = 1$. The energies E_0, E_1, ω_L and the q parameter are the same as for figure 2.

$E_2 = 2$. All energies are in units of Γ_1. It is obvious from figure 2 that the DC field coupling produces a zero in the spectrum. It is not a Fano-type zero, however, because we have assumed a high value of q. This zero falls on one of the Autler–Townes peaks produced by the strong laser field. Thus a third, very sharp peak accompanied by the zero arises in the spectrum. It represents the 'confluence of coherences' effect (Rzazewski and Eberly 1981, 1983). On the other hand, the photoelectron spectrum corresponds to the discrete atomic levels 'dressed' by the laser and DC fields. The quasi-energies of these levels are described by the zeros of the denominator $D(z)$ (equation (6)). One should bear in mind, however, that these quasi-energies are shifted by $E_0 + \omega_L$. In the case of weak DC coupling and a strong laser field the roots have the form given by equations (8). We note that all these quasi-energies are complex with non-zero values of their real parts. However, if the auto-ionising width of the level $|2\rangle$ is zero, one of the quasi-energies has a zero real part. This case corresponds to the 'population trapping' effect (Radmore and Knight 1984). It occurs if at least one of the quasi-energies has zero width. This situation corresponds to the existence of a long-lived 'dressed' state in our system which manifests itself as a sharp peak in the photoelectron spectrum. The effect vanishes with increasing auto-ionising width Γ_2. This is the same situation as that discussed by Leonski and Knight (1988) for decreasing effective coupling between the two auto-ionising levels as Γ_2 grows significantly.

Figure 3 shows the photoelectron spectrum for a weak laser field ($\Omega = 1$) and various auto-ionising widths Γ_2. The width Γ_1 and the q-parameter are the same as in figure 2. The energies are $E_0 = 0$, $E_1 = E_2 = 1$ and $\omega_L = 1$. For $\Gamma_2 = 0$ we observe a doublet induced by the DC electric field. Also, a DC field-induced zero appears in the spectrum. This zero is accompanied by a sharp peak. This again is the 'confluence of coherences' effect. For the case of a weak laser field we have found that one of the roots of $D(z)$ has its real part equal to zero and therefore the 'population trapping' effect appears. Since one of the 'dressed' states has a very long lifetime, a sharp peak appears in the spectrum. For non-zero values of the width Γ_2 ($\Gamma_2 = 0.1$ in figure 3) the zero vanishes from the spectrum. The latter becomes minimum with non-zero value. This is a result of the decrease in effective coupling between the auto-ionising states as Γ_2 grows, although the very sharp peak remains in the centre of the spectrum. This behaviour is due to the fact that the 'population trapping' is independent of the value of Γ_2 in the case of a weak laser field. One of the roots of $D(z)$ is equal to zero for any value of the auto-ionising width.

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References

Agarwal G S, Cooper J, Haan S L and Knight P L 1986 *Phys. Rev. Lett.* **56** 2586
Fano U 1961 *Phys. Rev.* **124** 1866
Lambropoulos P and Zoller P 1981 *Phys. Rev.* A **24** 379
Leoński W and Knight P L 1988 *J. Mod. Opt.* to be published
Leoński W, Tanaś R and Kielich 1988 *Programme and Abstracts OPTICS–ECOOSA 88 (Birmingham)* (London: IOP) p 181
Radmore P M and Knight P L 1984 *Phys. Lett.* **102A** 180
Rzazewski K and Eberly J H 1981 *Phys. Rev. Lett.* **47** 408
—— 1983 *Phys. Rev.* A **27** 2026