PHOTOELECTRON IONIZATION SPECTRA
IN A SYSTEM INTERACTING WITH A NEIGHBOR ATOM

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Abstract
We study long-time photoelectron ionization spectra of a system interacting with a neighbor two-level atom under the influence of a laser field. The system has at least a ground state and a continuum of states that are free with respect to one electron. In a weak light field, a Fano resonance is revealed. Also we consider an atomic autoionization level of the system, which leads to two Fano resonances under the influence of a weak field.

Keywords: photoelectron spectra, autoionization, dipole–dipole interaction.

1. Introduction

Along with bound states in atoms with at least two electrons, resonances may occur. The resonances change into states with one free electron after a very short time. This process is called autoionization of the atom. With a resurge of interest in the autoionization, Fano published an influential theoretical paper [1] illustrated by an analysis of the excitation of the $2s2p$ level of helium by electron bombardment. He derived that the natural line shape contains a zero. The optical absorption spectra of the rare gases were analyzed later [2]. Of many studies devoted to the mechanism of atomic autoionization, we can refer to [3]. A unified approach to the configuration interaction and the influence of strong lasers has been developed in [4]. Within this framework, the studies [5, 6] have been worked out. The quantum laser field has been included in [7] and the effect of the squeezed state has been treated in [8].

The Fano resonances can be observed also in other physical settings. At present, the Fano resonances in nanoscale structures [9] are of interest. This review article also provides historical remarks and many references. The combination of autoionization and the influence of lasers may be extended to a simultaneous autoionization, the influence of the laser, and the interaction with a neighbor two-level atom [10–13]. In the complicated analysis, the assumption of weak optical pumping has been helpful, which leads to a simpler behavior, cf. [4]. Complementary results have been obtained through numerical calculations.

In this paper, we add to the previous thorough analysis only the transformations of the Hamiltonian, which suggest two Fano zeros for the weak optical pumping. The third Fano zero is indicated, but cannot emerge in the photoelectron ionization spectrum. In Sec. 2, we recall known results on the systems with one and two autoionizing levels. In Sec. 3, we assume that such a system interacts with a neighbor two-level atom and restrict ourselves to the joint autoionizing state, which does not include an autoionizing level of the given system. In Sec. 4, we consider also the joint autoionizing states which comprise the autoionizing level of the given system. In Secs. 3 and 4, above all, we canonically transform the radiation energy, which has been newly formulated. In Sec. 5, we extend the canonical transformation of the system with one autoionizing level to the other components of the description. In Sec. 6, we conclude.
2. Previous Results

In this section, we review analyses of the atomic systems with one and two autoionizing levels. The two cases have been treated in [1], while in [4], the formalism employed in some other studies of the photoelectron spectra for the atoms in the laser fields was developed.

In [5], the atomic system with one autoionizing level is studied. A model of the autoionization is based on a coupling of this level to the continuum of states. The description further includes the ground state. Radiative transitions from this state to the continuum states and the radiative transition from the ground state to the autoionizing state are assumed.

The atomic system denoted by \( b \) is described by the Hamiltonian

\[
\hat{H} = \hat{H}_1(E)_C + \hat{V}_r,
\]

with

\[
\hat{H}_1(E)_C = E_b|1\rangle_b\langle 1| + \int E|E\rangle\langle E|dE + \int (V|E\rangle_b|1\rangle + \text{H.c.}) dE,
\]

where \( E_b \) means the excitation energy from the ground state \( |0\rangle_b \) into the autoionizing state \( |1\rangle_b \) of atom \( b \), \( V \equiv V(E) \) is a coupling function of the Coulomb configuration interaction between the autoionizing state \( |1\rangle_b \) and the continuum state \( |E\rangle \), and

\[
\hat{V}_r = [\mu_b\alpha_L \exp(-iE_L t)|1\rangle_b\langle 0| + \text{H.c.}] + \int [\mu\alpha_L \exp(-iE_L t)|E\rangle_b\langle 0| + \text{H.c.}] dE,
\]

with \( |0\rangle_b \) being the ground state of the atom \( b \), \( \mu_b \) the strength of optical excitation from this level into the autoionizing state \( |1\rangle_b \), \( \alpha_L \) the amplitude of the driving field, and \( E_L \) the driving frequency. Here \( \mu \equiv \mu (E) \) is the strength of optical excitation from the ground state \( |0\rangle_b \) into the continuum states \( |E\rangle \).

We note that

\[
\hat{H}_1(E)_C = \int E|E\rangle\langle E|dE,
\]

where \( |E\rangle \) are eigenstates of the energy operator (2). Since

\[
|E\rangle = b(E)|1\rangle_b + \int c(E,E')|E'\rangle dE',
\]

where \( b(E) = \frac{V^*(E)}{E - E_b + i\gamma_b}, \gamma_b = \pi|V(E)|^2 \), and \( c(E,E') = \frac{V(E')b(E)}{E - E' + i\varepsilon} + \delta(E - E'), \) we may rewrite \( \hat{V}_r \) in terms of the states \( |E\rangle \) as follows:

\[
\hat{V}_r = \int [\bar{\mu}(E)\alpha_L \exp(-iE_L t)|E\rangle_b\langle 0| + \text{H.c.}] dE.
\]

Here, \( \bar{\mu}(E) = \frac{\mu_b V^*(E)}{\epsilon_b(E) - i\gamma_b}, \epsilon_b(E) = \frac{E - E_b}{\gamma_b} \), and \( \gamma_b = \frac{\mu_b}{\pi\mu V^*} \).

It is obvious that the description of the driven system dynamics using the Schrödinger equation is oriented to the evolution of the state of the system \( |\psi\rangle(t) \). Now this state can be written in two ways,

\[
|\psi\rangle(t) = c_0(t)|0\rangle_b + c_1(t)|1\rangle_b + \int d(E,t)|E\rangle dE = c_0(t)|0\rangle_b + \int \tilde{d}(E,t)|E\rangle dE,
\]

where