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Ionization induced by strong electromagnetic field in low dimensional systems bound by short range forces

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ABSTRACT

Ionization processes for a two dimensional quantum dot subjected to combined electrostatic and alternating electric fields of the same direction are studied using quantum mechanical methods. We derive analytical equations for the ionization probability in dependence on characteristic parameters of the system for both extreme cases of a constant electric field and of a linearly polarized electromagnetic wave. The ionization probabilities for a superposition of dc and low frequency ac electric fields of the same direction are calculated. The impulse distribution of ionization probability for a system bound by short range forces is found for a superposition of constant and alternating fields. The total probability for this process per unit of time is derived within exponential accuracy. For the first time the influence of alternating electric field on electron tunneling probability induced by an electrostatic field is studied taking into account the pre-exponential term.

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1. Introduction

The advancements in semiconducting hetero-structure technology combined with large progress in powerful laser industry resulted into increased interest in theoretical and experimental aspects of low dimensional systems under impact of strong electromagnetic waves [1,2]. A number of new electronic devices based on such type of charge interaction become important for different applications. In particular, they include photodetectors on quantum well, various resonance electron tunneling diodes and triodes and Josephson junction devices.

The basement for the theoretical analysis of tunneling and photon induced ionization in low dimensional systems was laid down in previous publications [3–12]. For example, the results for one dimensional problem of a charged particle bound by short range forces [3–6] were used for calculation of photo-ionization probability in 1D quantum well subjected to a constant electric field [2].

Multiple photon atom ionization affected by superposition of electrostatic and alternating electric field of the same direction was previously studied in Refs. [13–18]. For the first time this problem was discussed semi quantitatively [15]. The refined approach for this phenomenon [14] derived differential probabilities for electron exit in systems bound by zero radius potential in the general case when the electrostatic field and electromagnetic wave polarization directions are not collinear. Particular interest was attracted to an orthogonal configuration. The results [14,15] demonstrated significant increase in ionization efficiency for a relatively weak alternating wave field in the presence of even moderate dc electric fields.

Non-perturbative calibration invariant model for the ionization process description in the case of both 1D and 3D systems with finite range binding potential was introduced in publications [13,18]. For short range forces the general characteristics of the ionization process were discussed in the case of superimposed dc and ac electric fields. However, the total ionization probability per time unit was not calculated in these papers.

Decay of shallow energy states resulting from short range attraction forces in the presence of electrostatic field and electromagnetic wave was previously analyzed in the publication [16]. In this case the ionization probability is found from the imaginary part of quasi-energy and like in Ref. [15] it is valid for the transverse fields when the interference contribution vanishes. The results [16] also demonstrate that even relatively weak electrostatic field affects drastically the probability of energy level ionization induced by the electromagnetic wave. For the interpretation of the results obtained, this work further introduced a new transition mechanism for the virtual state when electron absorbing certain number of wave quanta and acquiring energy $E_0 + k\omega < 0$ (ω is the wave frequency) tunnels in the dc electric field. This mechanism can be realised in the presence of both high frequency and static electric field.

For the most interesting case of collinear field directions the influence of alternating electric field on the particle quantum tunneling through energy barrier, semiconductor inter-band tunneling and above-barrier reflection, were analyzed in Ref. [17]

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by the complex trajectories method [19]. The probability for a particle to penetrate under a triangular ac field potential was calculated with exponential accuracy. It was shown that the probability for quasi-classical tunneling processes sharply increases under impact of time varying perturbation, and the changes in tunneling regime produced by growing amplitude of wave electric field were revealed. The results in Ref. [17] present ionization probability integrated over all energies and directions of emitted electrons. On the other hand for tunneling ionization some important information can be obtained from energy and angular distribution of created electrons [20–22], which were not studied in Ref. [17]. Regretfully, the paper [17] also misses the rigorous conditions when the obtained results are applicable, and the pre-exponential factor for total ionization probability per time unit was not calculated as well.

The importance of analytic results for the basic problem of electron transmission over a potential barrier in the presence of high-frequency electric field was pointed out in several previous publications [23–24]. However, no such expressions were presented.

Taking into account that the publications [13–18] predict significant increase in probability for classically forbidden processes under impact of electromagnetic wave, further investigation of ionization process for bound systems in variable electric field with a constant counterpart becomes very relevant.

In this work using the quantum mechanical method of Perelomov–Popov–Terentyev we aim to study the ionization processes induced by a superposition of electrostatic and alternating electric field of the same direction in low dimensional systems bound by short range forces.

The general expression for the system ionization probability is found in Section 2. This result is further used for the analytical equations describing the ionization rate for several extreme cases. The ionization rate for a two dimensional quantum dot interacting with the linearly polarized electromagnetic wave is calculated in Section 3.

In Section 4 we study the impact of alternating electric field on the electron tunneling probability for the 2D quantum dot in electrostatic field. For the results obtained we derive the applicability conditions and match that with the description based on the imaginary time method. The ionization probabilities for electrostatic field and also for a superposition of dc and low frequency ac electric fields of the same direction are calculated in Section 5. In the final section we present the discussion of the results obtained.

2. Calculation of ionization probability using the Perelomov–Popov–Terentyev method

Using the quantum mechanical method introduced in Ref. [6] we calculated the ionization probability for a system bound by short range forces and subjected to external electric field being a superposition of a static contribution with intensity F_1 and an alternating field with amplitude F_2 and frequency ω. The field vector potential dependent on time only, is taken like in Ref. [14]

$$A(t)=\left(-\frac{F_2\sin\,\omega t}{\omega}-F_1 t,0,0\right). \tag{1}$$

At the beginning let us consider a two dimensional case. In particular, this can be a 2D quantum dot. We will model the binding potential for this system by a potential well type [25]

$$U(\rho)=\begin{cases}-U_0,\rho=\sqrt{x^2+y^2}<a,\\ 0,\rho>a,\end{cases} \tag{2}$$

Here a is a radius of quantum dot. It is worth to mention that depending on the type of lateral binding potential the characteristic dimension of the quantum dot varies from tens to several hundreds nanometers, and the number of electrons can be controllably changed from few to several hundreds. The ground state eigenfunction for a time independent Schrodinger equation with electron energy $E_0=-\kappa^2/2$ and potential well (2) is given by [26]

$$\psi_0(\rho,t)=e^{i(\kappa^2/2)t}B\begin{cases}\frac{K_0(\kappa a)}{J_0(\lambda a)}J_0(\lambda\rho), & \rho<a,\\ K_0(\kappa\rho)\,, & \rho>a,\end{cases} \tag{3}$$

where $J_0(x)$ and $K_0(x)$ are Bessel and McDonald functions of zero order and the following notations are used:

$$\kappa=\sqrt{2|E_0|},\quad \lambda=\sqrt{2(U_0-|E_0|)},\quad B=\frac{1}{\sqrt{\pi}aK_1(\kappa a)}\left(\frac{U_0-|E_0|}{U_0}\right)^{1/2}. \tag{4}$$

The continuity condition for the wave function and its derivative at $\rho=a$ leads to equation

$$\frac{\lambda J_0^{'}(\lambda a)}{J_0(\lambda a)}=\frac{\kappa K_0^{'}(\kappa a)}{K_0(\kappa a)}, \tag{5}$$

which gives the energy E_0 $(-U_0<E_0<0)$ for the ground state of the electron in the quantum dot.

For a quasi-stationary regime the time dependent Schrodinger equation with the field (1) can be transformed into the following integral relation [6]

$$\psi(\vec{\rho},t)=-i\int_{-\infty}^{t}dt'\int_{-\infty}^{+\infty}G(\vec{\rho},t;\vec{\rho}\,',t')U(\rho')\psi(\vec{\rho}\,',t')d\vec{\rho}\,', \tag{6}$$

with

$$G(\vec{\rho},t;\vec{\rho}\,',t')=\frac{\theta(t-t')}{(2\pi)^2}\int dp_x dp_y \exp\left\{i\vec{\pi}\vec{\rho},(t)\vec{\rho}-i\vec{\pi}(t')\vec{\rho}\,'-\frac{i}{2}\int_{t'}^{t}\vec{\pi}^2(\tau)d\tau\right\}, \tag{7}$$

$$\vec{\pi}(t)=\vec{p}-\vec{A}(t)=\left(p_x+F_1 t+\frac{F_2}{\omega}\sin\,\omega t,p_y\right). \tag{8}$$

Further we assume that the condition

$$\max(F_1,F_2)a\ll\kappa^2<2U_0, \tag{9}$$

is satisfied, which means that inside the energy well the field (1) is a small perturbation. Then the exact wave function $\psi(\vec{\rho}\,',t')$ should have only negligibly small difference from $\psi_0(\vec{\rho}\,',t')$ defined by Eq. (3) inside the area of $\rho'<a$. Taking into account that for $\rho'>a$ the binding potential $U(\rho')$ vanishes, in the first approximation Eq. (6) for $\psi(\vec{\rho},t)$ gives the following relation:

$$\psi(\vec{\rho},t)=\frac{i}{(2\pi)^2}\int_{-\infty}^{+\infty}d\vec{p}\exp\left[i\vec{\rho}\vec{\pi}(t)-\frac{i}{2}\int_0^t\vec{\pi}^2(\tau)d\tau\right]G(t,p). \tag{10}$$

Here it is

$$G(t,p)=\int_{-\infty}^{t}dt' g(\vec{\pi}(t'))\exp\left\{\frac{i}{2}\int_0^{t'}\left[\vec{\pi}^2(\tau)+\kappa^2\right]d\tau\right\}, \tag{11}$$

and the value of $g(\boldsymbol{\pi}(t'))$ is related to Fourier transform for the space part of the wave function (3)

$$g(\vec{\pi}(t'))=1/2\left[\vec{\pi}^2(t')+\kappa^2\right]\varphi_0(\vec{\pi}(t')), \tag{12}$$

$$\varphi_0(\vec{\pi}(t'))=\int_{-\infty}^{+\infty}d\vec{\rho}\,'e^{-i\vec{\rho}\,'\vec{\pi}(t')}\varphi_0(\vec{\rho}\,'). \tag{13}$$

Further we introduce a phase variable as $\varphi=\omega t'$and transform Eq. (11) into

$$G(t,\vec{p})=\frac{1}{\omega}\int_{-\infty}^{\omega t}d\varphi g(\vec{\pi}(\varphi))\exp\left\{i\frac{\omega_0}{\omega}q(\varphi)\right\}, \tag{14}$$

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