Subthreshold excitation of atoms by electrons in an intense optical field

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The excitation involves the absorption of a large number of photons in an intense optical field in the subthreshold region of the electron energy. Processes of this type may play an important role in multiphoton ionization of atoms.

The intense light sources capable of producing optical fields comparable to atomic fields over a broad wavelength range (200–10^4 nm), which have recently appeared, open up the possibility of a systematic study of the nonlinear interactions of electrons and atoms with intense optical fields. Experiments[1–6] show that the nonlinear processes, involving the absorption of several hundred photons and the formation of multiply charged ions, occur at an anomalously high probability.

In this letter we take a theoretical look at the excitation of atoms and ions by electrons in an intense optical field. We find that the excitation process involves the absorption of a large number of photons in an intense optical field at electron energies in the subthreshold region. Processes of this type may play an important role in the multiphoton ionization of atoms, and it may be possible to carry out direct experimental studies of these processes.

Let us examine the problem of the scattering of an incident electron by an atom in a strong, linearly polarized optical field $\mathbf{E}(t) = \mathbf{E}_0\cos\omega t$. Using the standard expression (Ref. 7, for example) for the wave function of an electron in a uniform optical field, and treating the interaction of this electron with an atomic electron as a perturbation, we easily find the following expression for the cross section for the excitation of atomic level m from an initial state 0 (we are ignoring the effect of the optical field on the atomic electron):

$$d\sigma_{m0} = 8\pi\left(\frac{e^2}{\hbar v_0}\right)^2 \sum_n \frac{dq_n}{q_n^3} |F_{m0}(q_n) - \delta_{m,0}|^2 |J_n(\mathbf{q}_n \mathbf{A}_0)|^2$$

$$= \sum_n d\sigma^B_{m0}(p_0, p_n, q_n) |J_n(\mathbf{q}_n \mathbf{A}_0)|^2 ,$$

$$F_{m0}(q_n) = \langle \Psi_m | \exp(-i\mathbf{q}_n \mathbf{r} | \Psi_0 \rangle . \qquad (1)$$

Here p_0 and p_n are the initial and final moments of the electron (v_0 is the initial velocity); p_n is determined by the energy conservation law

$$E_m - E_0 + \frac{1}{2m}(p_n^2 - p_0^2) - \hbar\omega n = 0; \qquad (2)$$

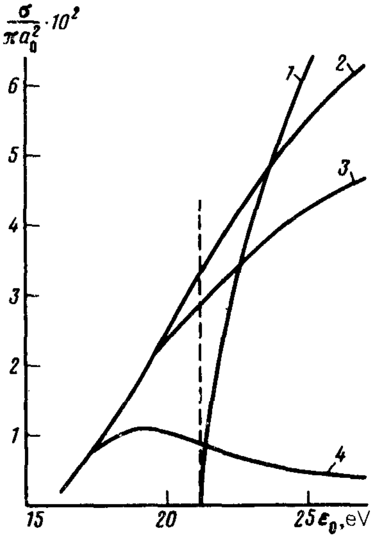

FIG. 1. Cross sections for excitation of the $1s^2$–$1s2p[^1P]$ transition of an He atom (the excitation energy is ~21.1 eV). 1—Born excitation cross section in the absence of a field; 2—excitation cross section in an optical field ($\omega = 0.1$ eV, $I = 1.6\times10^{10}$ W/cm) as calculated from (1) with $n = 0$–70; 3—$n = 20$–70; 4—$n = 40$–70.

$\hbar q_n = p_n - p_0$ is the momentum transfer; and Ψ_0, Ψ_m, E_0, and E_m are the wave functions and ionization potentials of the corresponding atomic states. The quantity $\mathbf{A}_0 = e\mathbf{E}_0/m\omega^2$ in the argument of Bessel function J_n represents the electron oscillation amplitude in the alternating field. Here $d\sigma^B_{m0}(p_0, p_n, q_n)$ is the Born excitation cross section. In deriving (1) we assumed that the field $\mathbf{E}_0$ and the momentum $\mathbf{p}_0$ are in the same direction. If the field $\mathbf{E}_0$ tends toward zero, we are left with only the term with $n = 0$ in the sum in (1), and this term becomes the ordinary Born excitation cross section.

Figure 1 shows results calculated on the cross section for the excitation by electrons of the $1s^2$–$1s2p[^1P]$ transition of a helium atom in an intense optical field (the transition energy is ~21.1 eV). The frequency of the light is $\omega = 0.1$ eV, and its intensity is $I = 1.6\times10^{10}$ W/cm^2; correspondingly, the electron oscillation amplitude in the field is $A_0 = 50a_0$, where $a_0 = 0.53\times10^{-8}$ cm is the atomic unit of length. It can be seen from this figure that even when the electron energy lies several electron volts below the threshold for excitation of the transition (the excitation processes cannot occur in the absence of the optical field), the cross section for excitation of the transition satisfies $\gtrsim 10^{-2}\pi a_0{}^2$ in an intense optical field, and the electron compensates for the lacking energy through the absorption of several tens of photons.

In calculating the cross sections for the excitation of ions by electrons in an intense optical field, we need to consider the Coulomb attraction of electrons to an ion. In this case, expression (1) remains valid, but we have to replace the Born cross section in it by the cross section calculated in the Born-Coulomb approximation, $d\sigma^{BC}_{m0}(p_0, p_n, q_n)$. This procedure can be justified by treating the excitation as a "jolting" of an electron in the presence of an optical field. The jolting approximation[8] is valid if the collision time is much shorter than the period of the electron oscillation in the field.

The Bessel functions which appear in expression (1) fall off exponentially at sufficiently large values of n ($n \gtrsim q_n A_0$). For estimates we can assume $q_n \sim k_0$ (k_0 is the wave number of an oscillating electron), and we can introduce the parameter $n_{\max} = A_0 k_0 = (A_0/a_0)(\epsilon_0/\mathrm{Ry})^{1/2}$, which determines the maximum number of photons involved in the excitation process (ϵ_0 is the energy of the electron, and Ry = 13.6 eV). At $n < n_{\max}$, the excitation (and ionization) processes involving n photons are of the same order of magnitude, while at $n \gg n_{\max}$ they are exponentially small. If we set $\epsilon_0 = l\hbar\omega$, then the condition under which electrons with this energy (and, automatically, electrons with higher energies) will participate in the excitation of the transition with an energy ΔE, absorbing $\Delta E/\hbar\omega$ photons in the process, is

$$\frac{A_0}{a_0} \sqrt{l} \left(\frac{\hbar\omega}{\mathrm{Ry}}\right)^{3/2} \left(\frac{\mathrm{Ry}}{\Delta E}\right) \gtrsim 1 .$$

This condition can be rewritten as

$$I_0 \gtrsim \frac{1}{16 l} \left(\frac{\hbar\omega}{\mathrm{Ry}}\right) \left(\frac{\Delta E}{\mathrm{Ry}}\right)^2 I_a \quad , \qquad (3)$$

where $I_a = cE_a^2/8\pi$ is the light intensity corresponding to the atomic field strength.

A study of the elementary interaction of an electron with an atom in an intense optical field may prove useful for analyzing a far more complex effect: multiphoton ionization of atoms.

One possible interpretation of multiphoton ionization, which shares some concepts with Refs. 5 and 9–16, runs as follows: The electrons which appear as a result of a single ionization of the atoms (this stage occurs essentially instantaneously at the light intensities used in the experiments) oscillate in the optical field, excite ions, and ionize them to higher degrees of ionization. Each new electron that appears becomes involved in this process. In the experiments (see the review in Ref. 5), for example, Ar^{6+} ions are detected ($\hbar\omega = 6.4$ eV). The ionization potential of Ar^{5+} ions is $\Delta E = 6.7$ Ry. In this case, condition (3)—for the participation of electrons with an energy $\epsilon_0 \gtrsim l\hbar\omega$ in the excitation process—becomes $I_0 \gtrsim (1/l) I_a$. This condition agrees in order of magnitude with the light intensity used in these experiments.

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