Impact self-ionization and self-excitation of an isolated atom in an ultrabright laser field

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(Submitted 15 April 1991)
Pis'ma Zh. Eksp. Teor. Fiz. **53**, No. 10, 493–495 (25 May 1991)

The impact self-ionization of an atom by its own electrons, as they oscillate in an ultrabright optical field, is examined theoretically. This process would outweigh other known processes over a wide range of parameter values of the pump light.

An ultrabright laser field (with an intensity $I \simeq 10^{17}$ W/cm^2) causes an instantaneous ionization of one or several of the higher-lying electrons of an atom in this field. It also transfers an oscillation energy of several kiloelectron volts to the electrons (the oscillation velocities are nonrelativistic). If the target is a dense gas, the electron oscillation amplitude in the gas may be larger than the mean free path. Electron-ion collisions would then be stimulated by the external laser filed. Since the incident electrons have a high kinetic energy, they cause a further impact ionization and also an excitation of the medium.[1-3] If the laser pulses have a temporal length shorter than the electron-ion relaxation time, the ions can be treated as cold. The excitation may be accompanied by the onset of a population inversion; a layout of this sort holds promise for developing x-ray and uv lasers of a new type.

If the gas density is instead quite low, electrons cannot collide with "other" ions. Presumably, only multiphoton ionization and multiphoton excitation should be observed in the gas in this case. Previous work has shown that this mechanism holds promise for producing an active medium for x-ray and uv lasers.[4,5] Even in a low-density gas, however, this is not the only mechanism for ionization and excitation. The electrons produced through above-threshold ionization of a given atom in a low-density gas do not immediately leave the vicinity of this atom; they instead oscillate in the laser field near "their own" atomic core. The motion of the electron is the sum of three components: an oscillatory component due to the field, a translational component, which the electron acquires during ionization, and a motion which arises because of the attraction by the atomic core. If only one electron is liberated in the ionization, the second of these components will in all cases ultimately determine whether the electron moves away from its own ion. If, on the other hand, several electrons are ionized in succession, the charge of the ion which is formed increases as this ionization continues. As a result, the first of the electrons to be formed are now bound, and their trajectories confined to the vicinity of the ion, for a certain time. Because of the strong laser field, the electrons execute a vibrational motion near the ion. The velocity at which they pass by the ion depends on the phase of the field at the instant at which the electron is formed. If an electron is formed at a time corresponding to a field maximum, the motion of the electron with respect to the ion will be symmetric, and its velocity as it passes near the ion will be at a maximum. In this case, an ionization and an excitation of the ion are possible. If the electron is instead formed near a minimum of the field, its motion with respect to the ion will be asymmetric, and its velocity near the ion will be comparatively low. At high field intensities, several electrons may form and may vibrate near a single multiply charged ion.

Let us assume that electron k is vibrating the x axis and that its motion is described by (we are ignoring the Coulomb interaction)

$$x_k = A\sin\omega t + x_k,$$

where A is the vibration amplitude, and x_k is the center of symmetry of the vibrations of the given electron. In general, this center will not coincide with the position of the ion, which we denote by x_0.

Because of the electron-electron interaction, the centers of the electron vibrations undergo a shift with respect to the ion comparatively rapidly; this shift naturally changes the velocity at which the electron passes near the ion. We denote by δ the change in the quantity $x_0 - x_k$ over a period. It is found from

$$\delta/A = (\pi^2 Z^2 m^2 \omega^4 / eE_m^3)^{1/3} \tag{1}$$

and can constitute a significant fraction of A. In expression (1), Z is the charge of the ion, e and m are the charge and mass of the electron, and ω and E_m are the frequency and maximum value of the pump field. Let us estimate δ/A. With $E_m = 5\times10^9$ V/cm (a light intensity $I = 3.3\times10^{16}$ W/cm^2), $\omega = 8\cdot10^{15}$ s^{-1}, $\lambda = 0.248$ μm (the output wavelength of a KrF laser), and $Z = 2$, we have $\delta/A \approx 0.4$. This result means that over a few vibration periods the velocity of the electron as it passes by the ion can change from the maximum value to the minimum value, and vice versa, so we can assume that this relative velocity becomes "stochastic" instantaneously. The velocity distribution of the electrons as they pass "near" an ion quickly reaches a steady state. By virtue of the discussion above, it is the same as the velocity distribution of the electrons at the time of the collision (the case of initially dense gases[3]):

$$f(v) = 2/\pi(1 - v^2/v_m^2)^{1/2}. \tag{2}$$

Here $v_m = eE_m/m\omega$.

Let us calculate the rates at which an individual ion is ionized and excited. These rates are equal to the number of collisions per unit time, multiplied by the probability for the corresponding process. The number of collisions is $2Z/T$ ($T = 2\pi/\omega$ is the period of the light from the pump laser). The probability for the process is the ratio of the corresponding cross section of the area of a circle whose radius is the characteristic distance at which the electron passes near the ion.

For circularly polarized pump light (or for a polarization ellipse which is not greatly prolate), the ion is displaced to the center of the ellipse, and the passing distance is on the order of the oscillation amplitude, i.e., extremely large. The processes which we have been discussing can occur again in this case ("remote" collisions[6] occur), but it is obvious that the probability for such processes will be small, on the order of $\sigma^2 m^2 \omega^4 / e^2 E_m^2$, where σ is the cross section for the process of interest.

The situation is different in the case of a linear polarization. In this case the passing distance ρ is determined by only the Coulomb interaction between the electron and the ion: $\rho = Tv_\perp/4$. Here $v_\perp$ is the velocity component of the electron transverse

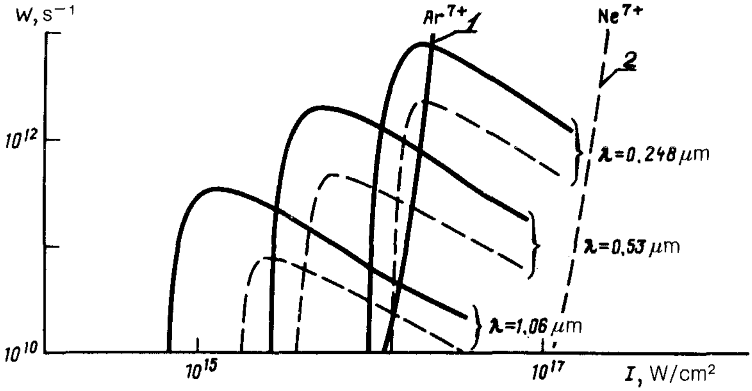

FIG. 1. Rate at which ions with a charge of seven are produced versus the intensity of the laser pump light (λ is the parameter). Solid lines—Ar^{7+}; lines 1 and 2—data of Ref. 4.

with respect to the field vector. In a first approximation we can write $mv_\perp^2/2 = Ze^2/\rho$, and

$$\rho = (Ze^2T^2/8m)^{1/3}. \tag{3}$$

The rates of the process of $Z+1$ ionization and of the corresponding excitation, W, are

$$W = \frac{8Z^{1/3}m^{2/3} < \sigma >}{\pi e^{4/3}T^{7/3}}. \tag{4}$$

The average of σ here is calculated with the function in (2).

To find some quantitative estimates of the rate of multiple ionization of an atom, we use the Thomson formula for the cross section. Figure 1 shows curves of the rates at which argon and neon ions with a charge of seven are produced in comparison with the rate of multiphoton ionization.[4]

Multiphoton ionization (and excitation) is thus predominant for the case of a circularly polarized pump in the visible or IR range. In the case of pumping by lasers with linearly polarized light in the blue, violet, or UV region, the predominant ionization mechanism will be the impact mechanism. One should of course allow for the circumstance that, at the light intensities under consideration in these estimates, the first two electrons would nevertheless appear as a result of multiphoton ionization (since the mechanism of classical above-threshold ionization could not operate); only then would the impact mechanism come into play.

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Translated by D. Parsons