

Above-barrier ionization of the hydrogen atom in a superstrong optical field

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The relative role of above-barrier ionization of the hydrogen atom in superstrong fields was investigated. It was found that for peak field intensity of $5 \cdot 10^{14}$ W/cm² the contribution of above-barrier ionization becomes important, if the width of the laser pulse is shorter than 100 fs. For stronger fields this limit will be higher.

Progress in laser technology in the last few years has made it possible to generate coherent electromagnetic radiation in the optical frequency range and with an electric field intensity of the order of 10^9 V/cm and higher. In such fields an atom comparatively rapidly ceases to be a bound atomic system, since the potential holding the electron near the atomic core drops below the binding energy E_i of the ground state of the atom. Thus, for example, for a hydrogen-like atom the atomic field strength F_a can be determined as the value at which the top of the potential barrier drops to the level of the binding energy E_i :¹

$$F_a = E_i^2 / 4Z. \quad (1)$$

Here Z is the charge of the atomic core. This expression can also be applied with good accuracy for nonhydrogenic atoms and ions.

The conditions for above-barrier ionization were satisfied in a number of recent experiments. Thus in Ref. 2 inert gases were ionized by neodymium laser radiation with wavelength $\lambda = 1.06 \mu\text{m}$ and radiation intensity up to $5 \cdot 10^{16}$ W/cm². This corresponds to field strengths of up to $6 \cdot 10^9$ V/cm. In accordance with Eq. (1) above-barrier ionization can occur in such fields in ions of inert gases with atomic cores with charges Z up to 7. Thus there is a need for a theoretical description of ionization of an atomic medium by superstrong optical radiation.

Up to now the theoretical description of the ionization of an atom (ion) by external electromagnetic radiation concerned two alternative situations—multiphoton ionization and tunneling ionization. For both cases the formulas describing the ionization probability when the intensity of the radiation field is not too strong are well known.

If, however, the field strength is high, then there exists another competing channel—the process of above-barrier ionization of the atom. How does this process occur? In Ref. 2 it is assumed that the probability for ionization of the atom becomes equal to unity as soon as the potential barrier drops below the binding energy of the atom. However this is only a model representation of the process of above-barrier ionization.

It is obvious that above-barrier ionization and sub-barrier tunneling processes transform smoothly into one another as the intensity of the external field is varied near the value of the atomic field strength F_a . A smooth transition also exists in the case of an alternating low-frequency field, when the adiabaticity parameter γ is small compared with unity.³ In the general case the theory of above-barrier ionization has not yet been developed.

In this paper we discuss the possibility of investigating

experimentally the process of above-barrier ionization. We determine the role of above-barrier ionization of an atom in the process of ionization against the background of tunneling ionization, which occurs at the points of the space-time distribution of laser radiation where the field is weak compared with the atomic value (1).

We shall perform specific calculations for the ionization of the hydrogen atom, for which numerical values of the ionization probability per unit time $w(F)$ as a function of the strength of the external field near the values of F_a and for different radiation frequencies have been obtained.³

To solve this problem it is necessary to compare the number of ions that are formed over the time of the laser pulse by means of above-barrier ionization with the total number of ions that can also be produced on the front of the space-time distribution by the mechanism of tunneling ionization through the potential barrier. We emphasize that we will not employ the tunneling formulas for the ionization probability (see Ref. 4 for a detailed discussion), since they are unreliable in the region where the electric field is not too weak compared with the atomic value F_a . In the calculations we shall take into account real experimental conditions: the space-time envelope of the laser pulse as well as saturation of the total ionization probability over the time of the laser pulse.

We shall assume that the form of the envelope of the laser pulse separates with respect to the spatial coordinates and the time:

$$I(x, y, z; t) = I_0 \varphi(x, y, z) \psi(t). \quad (2)$$

Here I_0 is the peak intensity of the radiation in the pulse. The temporal envelope $\psi(t)$ can be represented with good accuracy in the form of a Gaussian

$$\psi(t) = \exp(-t^2/t_l^2). \quad (3)$$

Here t_l is the length of the laser pulse.

In the case when the laser radiation is focused (which is always done in experiments in order to increase the radiation intensity) the function $\varphi(x, y, z)$ is often a Gaussian distribution. In the direction of propagation of the radiation (the z axis) the intensity distribution φ is close to uniform. Thus we have

$$\varphi(x, y, z) = \begin{cases} \exp(-r^2/R^2), & |z| < h/2, \\ 0, & |z| > h/2, \end{cases} \quad (4)$$

where $r^2 = x^2 + y^2$, R is the radius of the circle of focusing of the laser radiation, and h is the size of the focus.

The total number of ions formed during the time the laser pulse acts, taking into account the saturation of the

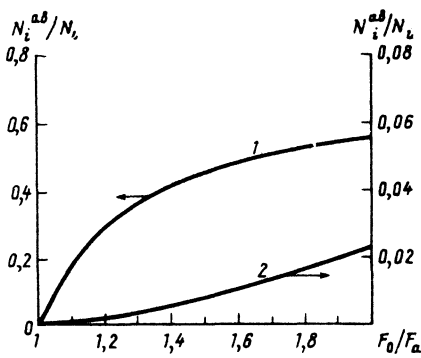


FIG. 1. The ratio of the number of ions N_i^{ab} formed via above-barrier ionization of the hydrogen atom by neodymium laser radiation to the total number N_i of ions formed over the time of the pulse t_l as a function of the peak strength of the electric field F_0 for two laser pulse widths: $t_l = 70$ fs (1) and $t_l = 700$ fs (2).

total ionization probability, can be written in the form

$$N_i = 2\pi n_0 h \int_0^\infty r dr \int_{-\infty}^\infty dt w(F(r, t)) \exp\left\{-\int_{-\infty}^t w(F(r, t')) dt'\right\}. \quad (5)$$

Here

$$F(r, t) = F_0 \exp(-t^2/2t_l^2 - r^2/2R^2); \quad (6)$$

n_0 is the density of atoms; F_0 is the peak value of the electric field strength, corresponding to the intensity I_0 ; $w(F)$ is the ionization probability per unit time, which for the hydrogen atom has been calculated numerically, as mentioned above, for field strengths $F_0 \leq 1/8$ (Ref. 3); (here and below we employ the atomic system of units $e = m_e = \hbar = 1$). In accordance with Eq. (1), for the hydrogen atom $F_a = 1/16$. Thus we can investigate the role of above-barrier ionization for field strengths in the range $F_a \leq F_0 \leq 2F_a$.

In the expression (6) for a given coordinate r there can exist a time t_c at which $F(r, t_c) = F_a$. In this case the integral over t in the expression (5) can be divided into three terms: the integrals from $-\infty$ to $-t_c$, from $-t_c$ to $+t_c$, and from $+t_c$ to $+\infty$. It is the second part, i.e., the integral from $-t_c$ up to $+t_c$, that determines the contribution of above-barrier ionization to the total number of ions formed over the time of the pulse. If, however, for a given value of r the time t_c does not exist, then this means that at the given point ions are produced only by means of tunneling ionization.

Following the indicated principle for calculating the number of ions formed, in this work we calculated numerically the relative contribution of the number of ions N_i^{ab} formed by above-barrier ionization [this is the integral in Eq. (5) from $-t_c$ to $+t_c$] to the total number of ions N_i formed. In the calculations we took the value of $w(F)$ from Ref. 3 for radiation wavelength $\lambda = 1.06 \mu\text{m}$. It is easy to verify that the ratio N_i^{ab}/N_i does not depend on the radius of

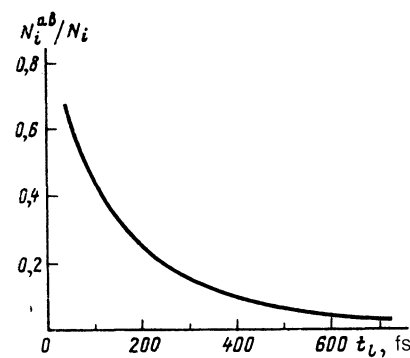


FIG. 2. The ratio N_i^{ab}/N_i as a function of the laser pulse width t_l for the peak intensity $I_0 = 5 \cdot 10^{14} \text{ W/cm}^2$.

focusing R but rather is determined only by the pulse length t_l and the peak field strength F_0 .

Figure 1 shows a plot of N_i^{ab}/N_i as a function of the peak strength of the external field F_0 for two different pulse lengths $t_l = 70$ fs and $t_l = 700$ fs. One can see that for a long pulse the contribution of above-barrier ionization to the ionization process is negligibly small. This means that in this region of space, where over the time of the pulse the field is stronger than the atomic value F_a , there is virtually no ionization, since there is enough time for ionization to occur on the leading edge of the radiation pulse. For a shorter pulse $t_l = 70$ fs ionization on the leading edge is less important, and for $F_0 = 2F_a = 6 \cdot 10^8 \text{ V/cm}$ the contribution of above-barrier ionization already reaches $\sim 50\%$. This corresponds to peak laser radiation intensity $I_0 = 5 \cdot 10^{14} \text{ W/cm}^2$.

Figure 2 shows a plot of N_i^{ab}/N_i as a function of the length of the laser pulse t_l for the peak field intensity $F_0 = 2F_a$. One can see that for this field strength the characteristic pulse length t_l for which the contribution of above-barrier ionization becomes significant (of the order of 50%) is equal to about 100 fs.

In summary, we can state that above-barrier ionization of atoms in superstrong fields becomes significant for short laser pulses, when there is not enough time for the total probability of ionization on the leading edge of the pulse to saturate. Thus for peak intensity $I_0 = 5 \cdot 10^{14} \text{ W/cm}^2$ the length should not exceed 100 fs in order of magnitude. For stronger fields this limit will be higher. We assume that the results obtained for hydrogen will not change much for ionization of other atoms in a superstrong optical field.

¹H. Bethe and E. Salpeter, *Quantum Mechanics of Atoms with One and Two Electrons*, Academic, N.Y., 1957.

²S. Augst, D. Strickland, D. D. Meyerhofer, S. L. Chin, and J. H. Eberly, *Phys. Rev. Lett.* **63**, 2212 (1989).

³M. Dorr, R. M. Potvliege, and R. Shakeshaft, *Phys. Rev. Lett.* **64**, 2003 (1990).

⁴N. B. Delone and V. P. Kraĭnov, *Atoms in a Strong Optical Field*, Springer-Verlag, N.Y., 1985.

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