On the role of inter-electron interaction in inner electron ionization by low-frequency strong field

M.Ya. Amusia [1]

The Racah Institute of Physics, The Hebrew University, Jerusalem 91904, Israel
Tel +972-2-658-4348, Fax +972-2-658-6347
E-mail: amusia@vms.huji.ac.il
[1] *A.F.Ioffe Physical-Technical Institute, St. Petersburg 194021, Russian Federation*

The aim of this presentation is to demonstrate that by taking into account the exchange between the outer and the inner atomic electrons the probability of inner electron ionization by a low-frequency field increases dramatically. A low frequency and high intensity external field creates a barrier for atomic particles to penetrate. Therefore our interest in this presentation is to clarify how the inter-electron Coulomb long range interaction affects the ability of a single or several particles to penetrate a potential barrier.

There exist some calculations, in which the action of strong laser field was taken into account numerically, by solving the corresponding Schrödinger equation. The complexity of this problem requires, however, considerable simplifications in the part of inter-electron interaction. In this presentation the main emphasize will be on the qualitative picture. From the real complexity of the multi-electron atom with its inter-electron interaction we will take into account only the exchange between atomic electrons.

To simplify the presentation further, let us consider instead of a multi-electron atom a two-level one, with the inner (i) and the outer (o) levels occupied. Denote the outer and inner electron ionization potentials as I_i and I_o, respectively. Assume, that $I_i \gg I_o$ and introduce the corresponding average momenta for the inner and outer electrons, α and β, as $\alpha = (2I_i)^{1/2}$ and $\beta = (2I_o)^{1/2}$. In our case one can substitute the high intensity low frequency laser field by a homogeneous electrical field of intensity $\mathbf{E}$, if the laser's frequency is much smaller than both I_i and I_o.

In order to estimate the probability of ionization of an atomic electron due to the presence of the field $\mathbf{E}$, we need to know the amplitude of the electrons wave function on the outer side of the barrier. These distances can be estimated as $R_{i,o} \sim I_{i,o}/|\mathbf{E}|$. Note that $R_i \gg R_o$. Far from the atom and neglecting the inter-electron exchange the electrons wave functions can be presented as

$$\varphi_i = A_i r^{1/\alpha} \exp(-\alpha r) \quad \text{and} \quad \varphi_o = A_o r^{1/\beta} \exp(-\beta r), \tag{1}$$

where $A_{i,o}$ are the normalization constants. They can be estimated as $A_i \approx \alpha^{3/2+1/\alpha}$ and $A_o \approx \beta^{3/2+1/\beta}$. As a result of (1), the probabilities to tunnel via the barrier for the inner and outer electrons $W_{i,o}$, which can be estimated as $W_{i,o} \approx \varphi_{i,o}(R_{i,o})|^2$, is given by the following expressions:

$$W_i = A_i^2 r^{2/\alpha} \exp(-2\alpha r) \quad \text{and} \quad W_o = A_o^2 r^{2/\beta} \exp(-2\beta r), \tag{2}$$

Thus, even for such a strong field that eliminates the outer electron with a unit probability, the inner electron ionization probability is exponentially small.

The situation is altered dramatically, if the exchange between atomic electrons is taken into account. It was demonstrated relatively long ago that the exchange modifies the asymptotic behavior of the one-electron states. Indeed, as a result of exchange the wave function of any atomic electron, even the innermost one, obtains an admixture of the outer electron wave function. This changes the asymptotic of the single-electron wave function qualitatively, adding to the ordinary asymptotic a contribution "borrowed" from the outermost electron. Considering large distance r, one can estimate the exchange term contribution and present $\tilde{\varphi}_i$ as

$$\tilde{\varphi}_i(r) \approx A_i(r^{1/\alpha} e^{-\alpha r} - B r^{1/\beta} e^{-\beta r}/r^2) \ . \tag{3}$$

Here B characterizes the strength of the interaction between i and o electrons. The probability to find the inner electron outside the potential barrier, i.e. at the distance R_i, is determined entirely by the second term in (2), if $I_i \gg I_o$, as it was assumed above.

The enhancement factor η of the inner electron ionization due to accounting for exchange can be estimated as

$$\eta \approx (B/I_i R_i^2)^2 R_i^{2/\beta} \exp 2\alpha R_i >>> 1 \ , \tag{4}$$

which for considerably remote levels i and o can be really giant because of the exponential factor, with $\alpha R_i \gg 1$. The account of exchange considerably increases the ratio ξ of i and o electrons ionization probabilities, which became much bigger than that without exchange, namely

$$\xi \approx (A_i B/A_o I_i R_i^2)^2 (R_i/R_o)^{2/\beta} \exp(-2\beta R_i) \tag{5}$$

instead of $\eta_o \approx (A_i/A_o)^2 (R_i^{2/\alpha}/R_o^{2/\beta}) \exp(-2\alpha R_i)$.

Note, that the exponent $2\beta R_i$ is much smaller than $2\alpha R_i$. As an example, let us consider a case, when $I_i = 10, I_o = 1$ and where $\mathbf{E}$, which determines R_i and R_o, is equal to an atomic unit. Then $\eta \approx 10^{10}$, it is tremendous, while $\xi \approx 10^{-3}$ is not too small.

An essential feature of the exchange effect is its coherency. Indeed, if at the level o it would be N_o identical electrons, the second term in (3) would acquire a factor N_o, thus increasing the inner electron ionization probability by N_o^2.

The physical meaning of the presented results is that the inner electron is removed off the atom not by the external high intensity field but under the coherent action of outer electrons turned into motion by that field. The creation of inner vacancy can be detected by observing the emission of a characteristic X-ray line.