Atomic antenna

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A new mechanism for the absorption of photons of a low-frequency field by an atom is proposed: an "atomic antenna." This mechanism raises the intensity of multiphoton processes by many orders of magnitude. This is true in particular of multiple ionization and of ionization far from the threshold.

Let us examine the interaction of an atom with laser light whose frequency ω and field strength F/e are small at the atomic scales: $\hbar\omega \ll I$ and $F \ll e^2/a_0^2$, where I is the ionization potential, and a_0 the first Bohr radius. We are interested in those excitations of the atom by the field which require a large—multiphoton—absorption of energy. One such case is ionization of the atom with a fast photoelectron, with $p^2/2m \gg \hbar\omega$; another is ionization of an atom involving excitation of the ion, in particular, multiple ionization.

Experiments have yielded the surprising result that such processes occur with a large probability.[1–9] The gap between the experimental data and the existing theory is wide; in the case discussed in Ref. 6, for example, it reaches 10^{40}.

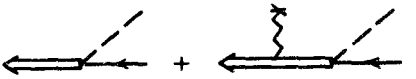
In this letter we wish to propose a new and effective absorption mechanism: the "atomic antenna." Let us outline this mechanism. We assume that an atom is ionized, absorbing the minimum necessary number of photons, $\approx I/\hbar\omega$. We assume that the photoelectron oscillates in the electric field of the wave. The kinetic energy of the oscillations in an intense laser field can be large: $F^2/2m\omega^2 \gg \hbar\omega$. We now assume that the photoelectron is scattered by the parent ion. As a result, the energy of the oscillations can be converted into energy of the translational motion of the electron, or it may be expended on exciting or ionizing the ion. The electron in this process plays the role of an absorber of field energy—the role of an antenna. An important point is that this absorption occurs intensely, since the frequency of the electron oscillations is equal to the field frequency ω. Scattering by the ion is also highly probable, for this scattering is not adiabatic. The probability for the absorption of a large amount of energy is thus high.

This study has shown, for the first time, that the amplitude of the multiphoton process can be factorized into the amplitude for threshold ionization and the amplitude for the scattering of the electron by the ion in the laser field. Consequently, the process occurs in two steps. The physical picture drawn above is a qualitative interpretation of the results which have been found. The property found for the amplitude is extremely general and does not depend on the particular features of the atomic structure. The relations which have been derived can be used to predict the spectral and angular distributions of the photoelectrons.

We turn now to the calculations. We restrict the calculations to the case in which

the field is linearly polarized. We first consider the problem of the photoelectron spectrum far from the threshold, with $p^2/2m \gg \hbar\omega$, where $\mathbf{p}$ is the momentum of the translational motion of the ejected electron. We write the ionization amplitude as a power series in the potential describing the interaction of the outgoing electron with the ion:

$$A(\mathbf{p}) = A_0(\mathbf{p}) + A_1(\mathbf{p}) + \ldots =$$



$$+ \ldots \qquad (1)$$

Here a thin line describes the motion of the electron in the atom, a double line the behavior of the electron in the field of the wave, and the wavy line the ion potential. The amplitude $A_0(\mathbf{p})$ was first calculated in the well-known paper by Keldysh.[10] This amplitude falls off rapidly, exponentially, with increasing energy of the electron.

In calculating A_1 we note that our problem has two length scales: small atomic distances and the large oscillation amplitude of the electron in the field: $F/m\omega^2 \gg a_0$. This circumstance allows us to reduce the expression for A_1 to a very simple factorized form ($e = \hbar = m = 1$):

$$A_1(\mathbf{p}) = \sum_n [A_0(-\mathbf{p}_n) f_n(-\mathbf{p}_n, \mathbf{p}) + A_0(\mathbf{p}_n) f_n(\mathbf{p}_n, \mathbf{p})]/R. \qquad (2)$$

Here $\mathbf{p}_n = (p^2 - 2n\omega)^{1/2}\mathbf{F}/F$ is the momentum of the photoelectron in the intermediate state. The sum over n is dominated by processes in which this momentum is small: $p_n \ll p$. The amplitude $A_0(\mathbf{p}_n)$ is therefore the amplitude for ionization near the threshold; it does not decrease with increasing $\mathbf{p}$. The quantity $f_n(\mathbf{p}_n, \mathbf{p})$ in (2) is the amplitude for the scattering of the electron by the ion, in a process which is accompanied by the absorption of n photons and a corresponding acceleration of the electron:

$$f_n(\mathbf{p}_n, \mathbf{p}) = -\frac{1}{2\pi} \langle \mathbf{p} | U | \mathbf{p}_n \rangle (-i)^n e^{iz} J_n(z). \qquad (3)$$

Here U is the potential of the ion, $J_n(z)$ is the Bessel function, and $z = (\mathbf{p} - \mathbf{p}_n)F/\omega^2$. The factor R in (2) is given by $R = F\omega^{-2}(1+\gamma^2)^{1/2}$, where $\gamma = (2I)^{1/2}\omega/F$ is the adiabatic parameter. The two terms in square brackets in (2) correspond to two saddle points, $\omega t_{1,2} = i\,\mathrm{arsh}\,\gamma$, $\pi + i\,\mathrm{arsh}\,\gamma$, in the complex plane of the time at which the electron escapes from the atom.

From (2) and (3) we find that as the energy increases, the amplitude $A_1(\mathbf{p})$ falls off slowly, in a power-law fashion, as long as the following inequality holds:

$$n \leqslant \nu \cos^2\theta, \qquad (4)$$

where n is the number of photons absorbed above the ionization threshold, $\nu = 2F^2/\omega^3$, and $\cos\theta = p\cdot\mathbf{F}/pF$. Condition (4) determines the spectral-angular region in which the antenna absorption mechanism is dominant: $|A_1(\mathbf{p})| \gg |A_0(\mathbf{p})|$.

In a similar way, we examine the problem of ionization accompanied by the excitation of an ion, in particular, multiple ionization. Equation (2) remains valid in this case if we understand f_n as the amplitude for the inelastic scattering of the electron by the ion. The antenna mechanism turns out to be effective if the ion excitation

energy Δ is limited by the condition $\Delta \leqslant \nu\omega/4$. Interestingly, the excitation of the ion must be accompanied by a simultaneous acceleration of the electron which is initially ejected; the energy that it absorbs is also limited by the condition $p^2/2 \ll \nu\omega/4$. This effect is specific to the antenna absorption mechanism, so that its experimental observation would be extremely interesting.

Luk *et al.*[8] and Szöke and Rhodes[11] have offered the hypothesis that the polarizability of the outer shells of an atom plays an important role in multiple ionization processes. That hypothesis is based on a model. An analysis shows that in an intense field the multiphoton problem has an exact solution in a sense: A complicated entity—an ionization amplitude—can be expressed in terms of a far simpler scattering amplitude.

In this letter we have examined the antenna absorption mechanism in the first order of a perturbation theory which is applicable under the condition $\gamma \leqslant 1$. The violation of this condition and also the case in which the absorbed energy exceeds $\gamma\omega$ require a higher-order perturbation theory. There is the hope that the physics of the process will remain largely the same when this switch is made.

In the static limit, the ionization mechanism which we have been discussing here seems to have many features in common with the set of ideas in Refs. 12–14.

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