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Absorption of Femtosecond Laser Pulses by a Negative Hydrogen Ion

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ABSTRACT: The work is dedicated to the theoretical study of absorption of femtosecond laser pulses by a negative ion of a hydrogen atom H^-. The paper considers the dependence of the total probability of the process on the parameters of a corrected Gaussian pulse (carrier frequency, duration). Besides, the spectra of photoelectrons ejected from an ion under the action of laser pulses of different durations and initial phases are calculated.

The development of technology for generation of ultrashort (including femtosecond) laser pulses with controlled parameters [1-3] has set the problem of adequate description of processes of interaction of ultrashort pulses (USP) with a substance [4]. One of important objects of such an interaction, both from the fundamental point of view and in terms of applications, is a negative ion of atomic hydrogen. The process of photodetachment of an electron from H^- under the action of a laser pulse of duration 4 fs at a fixed central wavelength of 800 nm was considered in the paper [5]. Photoelectron spectra resulting from the action of pulses with different initial phases as well as from the action of a series of identical pulses were calculated.

The purpose of the present work is to calculate and to analyze the total and differential probabilities of USP absorption (during the action of a pulse) by a H^- ion depending on the carrier frequency and the duration of the pulse.

The probability of photoabsorption during the action of an electromagnetic pulse looks like [6]

$$W_{abs}(\omega,\tau)=\frac{c}{4\pi^2}\int_A^\infty \sigma_{abs}(w)\frac{\left|E(w,\omega,\tau)\right|^2}{\hbar w}dw, \tag{1}$$

where c is the velocity of light, $\sigma_{abs}(w)$ is the photoabsorption cross-section, $E(w,\omega,\tau)$ is the Fourier transform of the strength of the electric field in a pulse of duration τ at a carrier frequency ω, A = 0.754 eV is the energy of electron affinity of a hydrogen atom.

The differential probability of photodetachment of an electron with an energy ε from a negative hydrogen ion is easily obtained from the formula (1) in view of the energy conservation law $\hbar w = A+\varepsilon$:

$$\frac{dW}{d\varepsilon}=\frac{c}{4\pi^2}\sigma_{abs}\left(\frac{\varepsilon+A}{\hbar}\right)\frac{\left|E\left((\varepsilon+A)/\hbar,\omega,\tau\right)\right|^2}{\varepsilon+A}, \tag{2}$$

where ε is the photoelectron energy.

According to the optical theorem, the photoabsorption cross-section is expressed in terms of the imaginary part of the dynamic polarizability of the target α(ω) as follows:

$$\sigma_{abs}(\omega)=\frac{4\pi\omega}{c}\mathrm{Im}\alpha(\omega). \tag{3}$$

In the case under consideration, when the target is a negative ion of atomic hydrogen, for the imaginary part of its dynamic polarizability the expression [7] is true (hereafter we use atomic units):

$$\mathrm{Im}\,\alpha(\omega)\cong 3.73\ \frac{(\omega-A)^{3/2}}{\omega^4}\ \ \sqrt{A}\ \ \theta(\omega-A) \tag{4}$$

here θ(w) is the Heaviside function.

The cross-section of photoabsorption of a negative hydrogen ion calculated by the formulas (3)-(4) is presented in Fig. 1. It should be noted that a characteristic feature of the ion under consideration is the absence of a discrete energy spectrum, so the photoabsorption cross-section has a nonzero value only for frequencies ω > A. It is also essential that the maximum of the absorption spectrum falls on frequencies ω_{max} > A in contrast to a neutral hydrogen atom, in which, as is known, ω_{max} coincides with the threshold frequency.

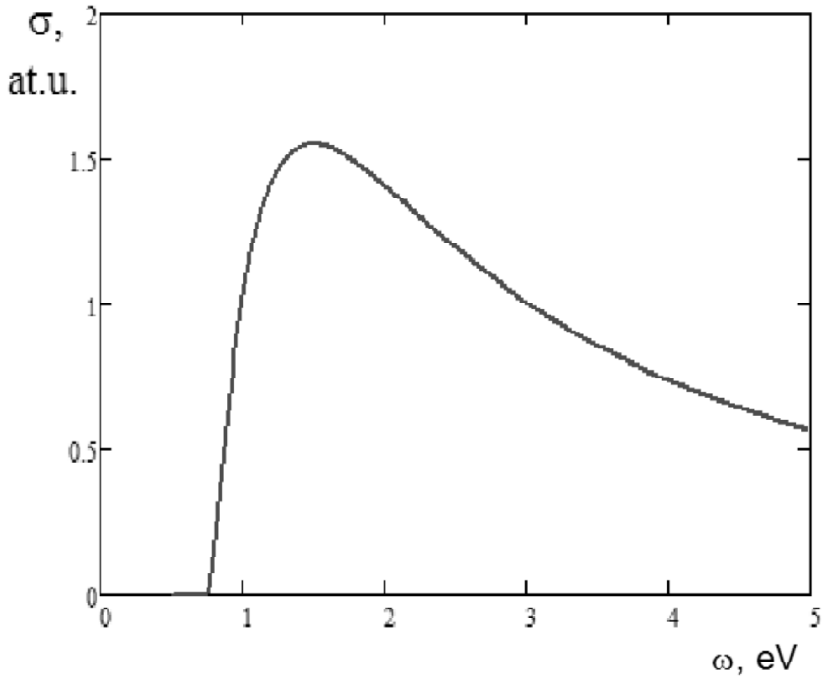

Figure 1: The cross-section of photoabsorption by a negative ion of a hydrogen atom

Further we will consider absorption of a laser pulse of a corrected Gaussian shape (CGP), the Fourier transform of which looks like [8]

$$E_{cor}(w,\omega,\tau,\varphi)=i\,E_0\,\tau\sqrt{\frac{\pi}{2}}\frac{w^2\tau^2}{1+\omega^2\tau^2}\left\{e^{-i\varphi-(\omega-w)^2\tau^2/2}-e^{i\varphi-(\omega+w)^2\tau^2/2}\right\}, \tag{5}$$

where E_0, τ, ω are the amplitude, the duration, and the carrier frequency of a pulse, *w* is the "current" frequency, φ is the carrier phase with respect to the envelope. In the limit of long pulses (5) coincides with the expression for a usual Gaussian pulse. A distinguishing feature of the Fourier transform (5) is the absence of a constant component in it: $E_{cor}(w=0,\omega,\tau,\varphi)=0$.

The calculations of the photoabsorption probability were carried out for the amplitude of the electric field $E_0 = 3\cdot10^{-3}$ a.u.

The results of calculations for the total probability of photoabsorption (during the action of a pulse) are presented in Figs. 2-4.

Shown in Fig. 2 is the process probability normalized to the pulse duration ($w_{abs} = W_{abs}/\tau$) as a function of the carrier frequency for different values of the parameter τ of the subfemtosecond range of durations.

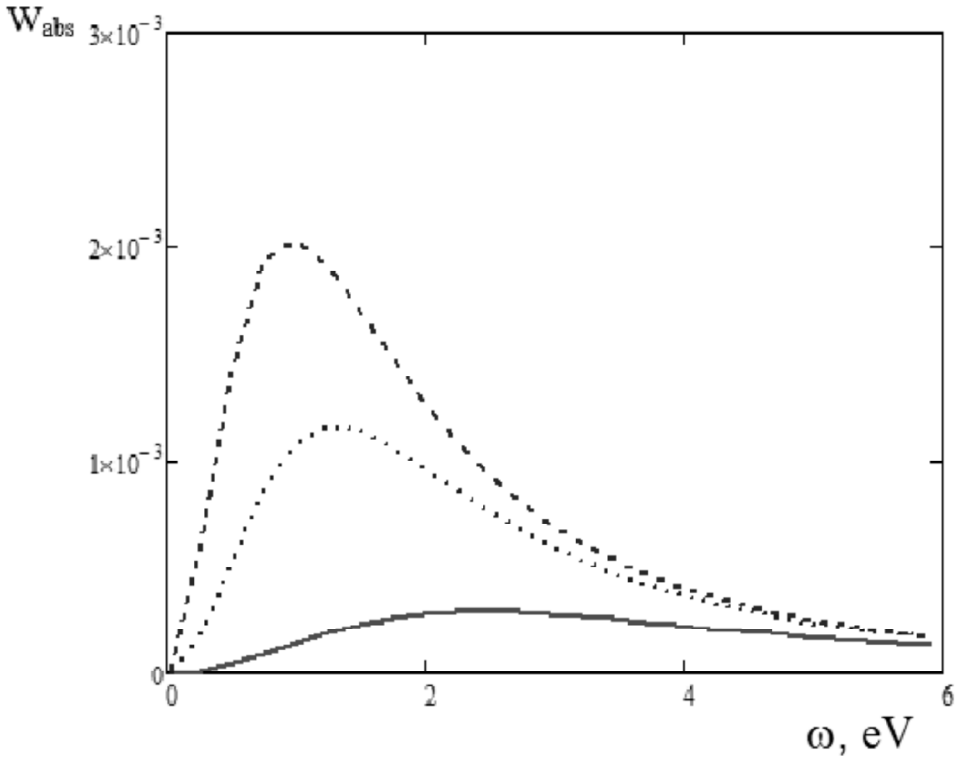

Figure 2: The probability of USP photoabsorption normalized to the pulse duration as a function of the CGP carrier frequency for small values of τ: solid curve - τ = 0.24 fs, dotted curve - τ = 0.48 fs, dashed curve - τ = 0.72 fs

It is seen that in the case under consideration the photoabsorption probability is different from zero even for subthreshold values of the carrier frequency, the spectral maximum being shifted to the region of lower frequencies with increasing pulse duration. Presented in Fig. 3 are similar dependences for longer laser pulses. It is seen that as the parameter τ increases, the corresponding curve approximates to the shape of the photoabsorption spectrum (Fig. 1), so the threshold frequency of the process shows itself in the vicinity of the value A = 0.754 eV. This is connected with the fact that in the limit of long pulses the squared absolute value of the Fourier transform of the electric field is proportional to the delta function of the difference of the current and carrier frequencies:

$$\left|E(w,\omega,\tau>>1/\omega)\right|^2 \propto \tau E_0^2 \delta(w-\omega). \tag{6}$$

As a result, the integral in the formula (1) is taken easily, and the photoabsorption probability is found to be proportional to the cross-section (accurate to the factor 1/ω) and increases linearly with pulse duration:

$$W_{abs}(\omega,\tau) \propto \frac{c}{4\pi^2}\frac{\tau E_0^2}{\omega}\sigma_{abs}(\omega). \tag{7}$$

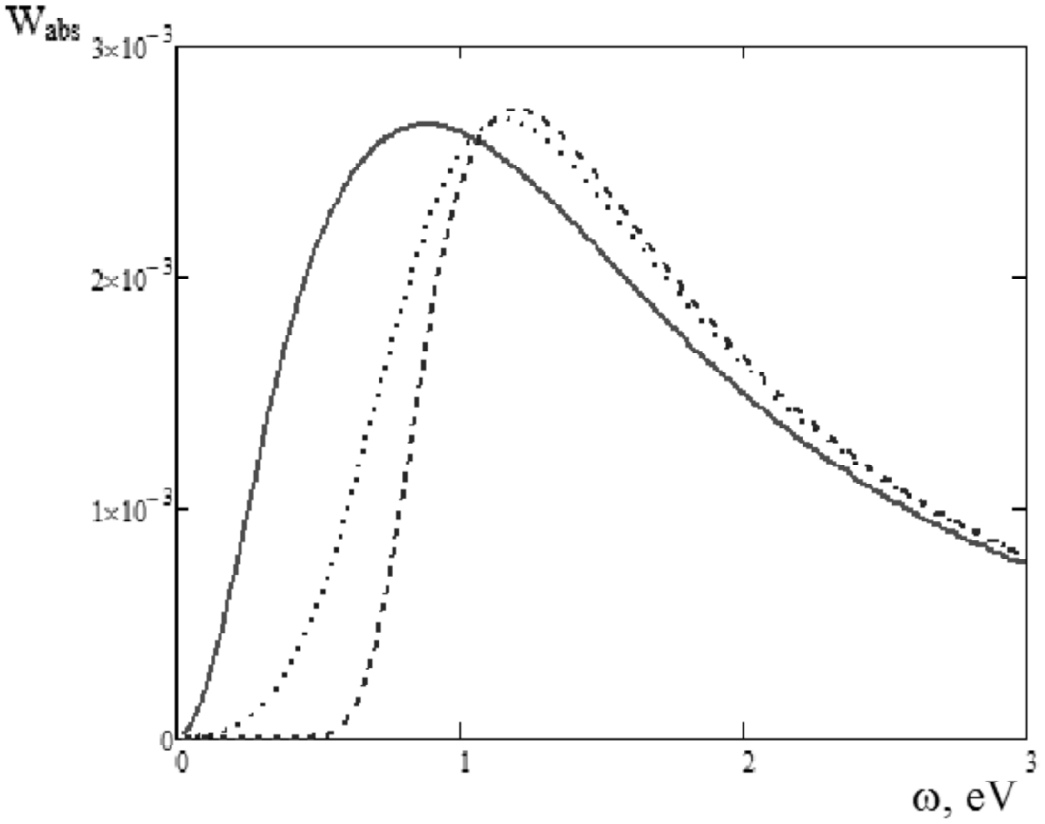

Figure 3: The probability of USP photoabsorption normalized to the pulse duration as a function of the CGP carrier frequency for larger values of τ: solid curve - τ = 1.2 fs, dotted curve - τ = 2.4 fs, dashed curve - τ = 4.8 fs

Presented in Fig. 4 is the photoabsorption probability as a function of the pulse duration for different carrier frequencies. It is seen that when the carrier frequency decreases below the threshold frequency, the corresponding dependence tends to zero at long durations τ. On the contrary, at frequencies higher than the threshold frequency the photoabsorption probability increases linearly with increasing τ. These qualitative regularities follow also from the formula (6). Really, in the limit of long pulses the photoabsorption probability, as was already noted above, is proportional to the process cross-section presented in Fig. 1 according to the formula (7).

In the limit of short (subfemtosecond) pulses the photoabsorption probability practically does not depend on the carrier frequency and increases by the power law with CGP duration.

The calculation of the probability of photodetachment of an electron with an energy ε in the final state was carried out by the formula (2) for a fixed carrier frequency corresponding to the central wavelength of Ti:Al_2O_3 laser amplification (λ = 800 nm).

Figs. 5-6 demonstrate the calculated photoelectron spectra for two values of the initial phase (Fig. 5) and for different CGP durations (Fig. 6).

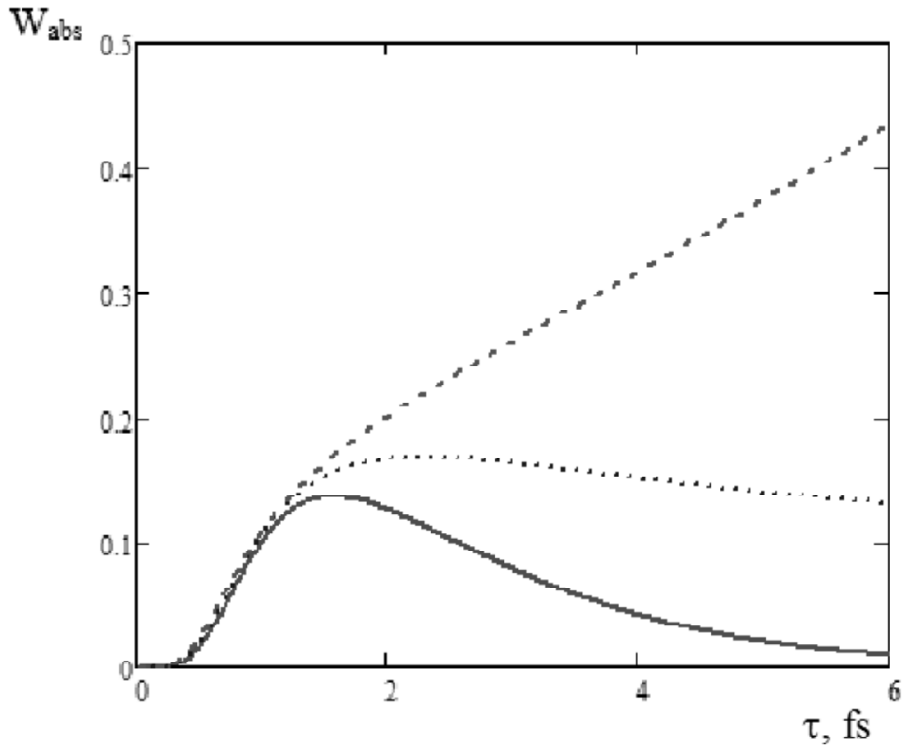

Figure 4: The probability of CGP photoabsorption as a function of the pulse duration for different carrier frequencies: solid curve - ω = 0.626 eV, dotted curve - ω = 0.754 eV, dashed curve - ω = 0.898 eV

The dependence of the photoelectron spectrum on the initial phase is presented for a pulse duration of 0.24 fs (10 a.u.). It is seen that for so short pulses the phase has a strong effect on the spectrum. However, for long $\tau > 25$ a.u. this dependence practically disappears throughout the range of photoelectron energies.

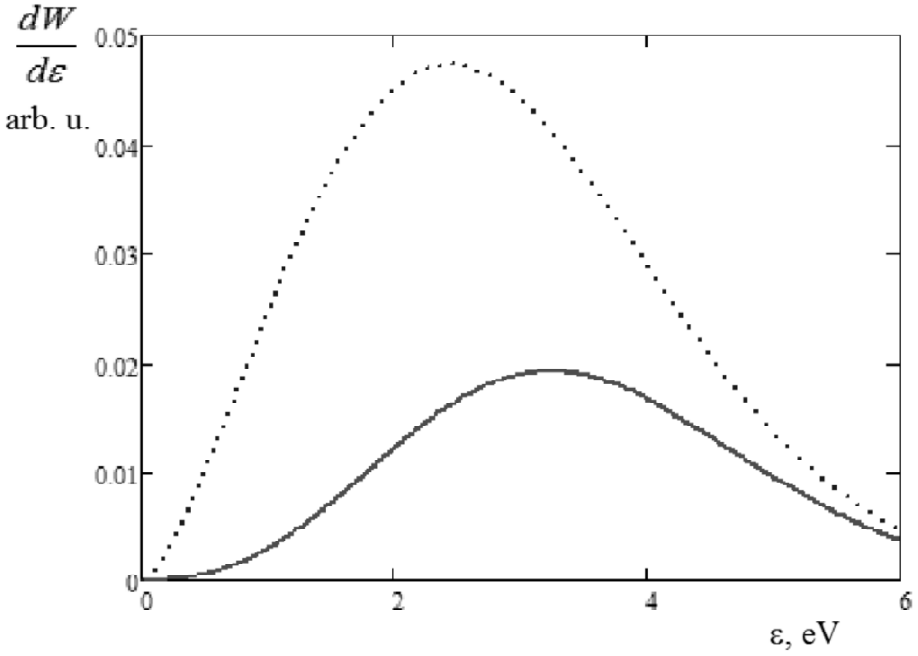

Figure 5: The spectra of a photoelectron ejected from the target under the action of an USP of duration τ = 0.24 fs at the carrier frequency ω = 1.55 eV for two values of the initial phase: φ = 0 (solid curve), φ = π/2 (dotted curve)

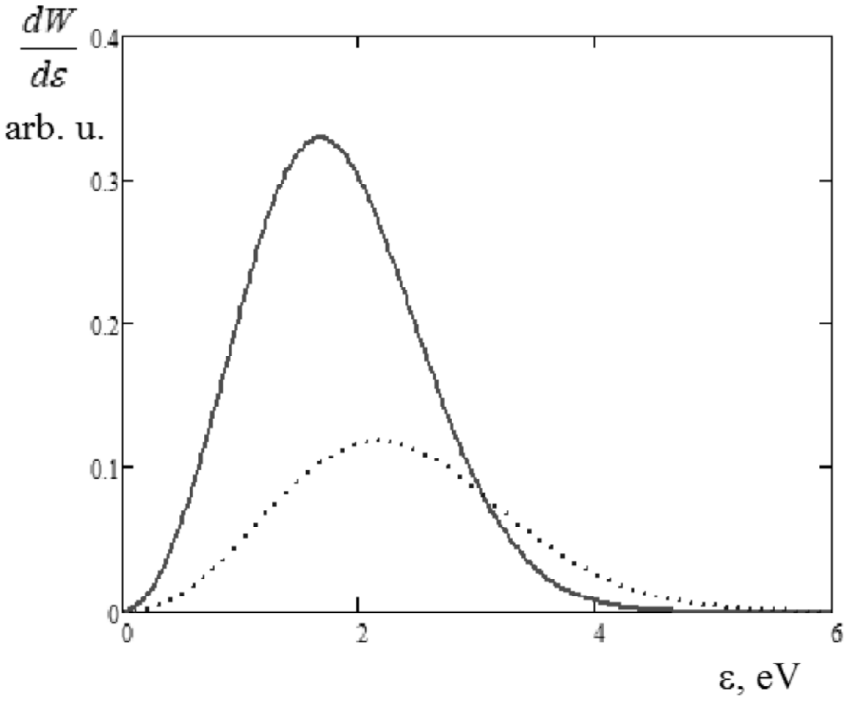

Figure 6: The spectra of a photoelectron ejected from the target under the action of an USP at the carrier frequency ω = 1.55 eV for two values of the pulse duration: τ = 0.48 fs (solid curve), τ = 0.36 fs (dotted curve); φ = 0

As seen from Fig. 6, the dependence of the photoelectron spectrum on the pulse duration is also considerable for sufficiently small t (in the subfemtosecond range). In case of long pulses (for $\omega > A$), the photoelectron spectrum shape practically does not depend on τ, and only the maximum value of the probability increases.

Thus in the work the characteristic features of the probability of absorption of a femtosecond laser pulse by a negative ion of atomic hydrogen during the action of a pulse were calculated and analyzed. In particular, the nonlinear dependence of the photoabsorption probability on the pulse duration for carrier frequencies lower than the threshold value was demonstrated. It was shown that the photoabsorption spectrum depends considerably on the pulse duration. Thus for sufficiently short pulses the photoabsorption probability has an appreciable value in the subthreshold region as well. At the same time, for $\tau > 5$ fs the photoabsorption spectrum shape (the dependence of the process probability on the carrier frequency of a laser pulse) practically coincides with the shape of the photoabsorption cross-section. The dependence of the photoelectron spectrum on the initial phase is considerable only for sufficiently short pulses $\tau < 0.4$ fs. In case of large duration values, the initial phase has no effect on the photoelectron spectrum.

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