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Scattering of Ultrashort Electromagnetic Pulses on Fano Resonance

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ABSTRACT: The paper is devoted to the theoretical investigation of scattering of ultrashort pulses (USP) with Gaussian envelope on Fano resonance in terms of total probability of the process during all time of pulse action. Dependences of this probability upon pulse duration and carrier frequency are calculated for the helium atom in the vicinity of the lowest auotoionized state. Besides the analytical expression of dynamical polarizability near own frequency of Fano resonance is obtained and spectral scattering cross section is calculated.

Key words: Fano resonance, radiation scattering, ultrashort pulse, dynamical polarizability

Ultrafast radiation phenomena in the vicinity of Fano resonance are attracted much attention of researchers in recent years due to rapid development of ultrashort pulse generation technology [1].

Ultrafast buildup of Fano resonance in time domain is observed in paper [2] by interrupting the autoionization process with the use of strong near infrared laser field. Theory of time-dependent formation of the profile of autoionized state in helium excited by a short laser pulse is developed in paper [3] with the help of analytical and numerical approaches.

Effects of ultrashort laser pulse duration on Fano resonances in atomic absorption spectra are investigated theoretically in paper [4] in terms of total absorption probability of USP by He atom.

Let us consider general case when Fano resonance in photo-absorption cross section is given by well-known expression [5]:

$$\sigma_{abs}(\omega) = \sigma_0 \frac{\left(q + \dfrac{2(\omega-\omega_0)}{\Gamma}\right)^2}{1 + \left(\dfrac{2(\omega-\omega_0)}{\Gamma}\right)^2} \tag{1}$$

here ω_0 is own frequency and Γ is the spectral width of the resonance, q is Fano parameter, σ_0 is photo-absorption cross section without contribution of autoionized state. We suppose that $\sigma_0 \cong const$

In the case of USP we describe the scattering by the probability of the process during all time of the pulse action W. The expression for W in the first order of the perturbation theory has the form [6]:

$$W(\tau) = \frac{c}{4\pi^2} \int_0^\infty \sigma_{sc}(\omega') \frac{\left|E(\omega',\tau)\right|^2}{\hbar\omega'} d\omega', \tag{2}$$

here c is light velocity, ω' is current frequency, $\sigma_{sc}(\omega')$ is light scattering cross section, $E(\omega', \tau)$ is Fourier transform of electric field strength in the pulse, τ is pulse duration. Naturally, expression (1) has a sense for $W < 1$.

In dipole approximation for light scattering cross section one has:

$$\sigma_{sc}(\omega) = \frac{8}{3}\frac{\pi}{}\frac{\omega^4}{c^4}\left|\beta(\omega)\right|^2. \quad (3)$$

Here $\beta(\omega)$ is dynamical polarizability of the target. To find the imaginary part of dynamic polarizability we use the optical theorem:

$$\mathrm{Im}\{\beta(\omega)\} = \frac{c}{4\pi\omega}\sigma_{abs}(\omega) \quad (4)$$

and for real part we use Kramers-Kronig relation in the following form:

$$\mathrm{Re}\{\beta(\omega)\} = \frac{c}{2\pi^2}\int_0^{+\infty}\frac{\sigma_{abs}(\omega') - \sigma_{abs}(\omega)}{\omega'^2 - \omega^2}d\omega'. \quad (6)$$

Substituting formula (1) into (6) we obtain analytical expression for real part of dynamical polarizability in the vicinity of Fano resonance:

$$\mathrm{Re}\{\beta(\omega)\} = \frac{c\sigma_0}{4\pi^2\Gamma\left[\frac{(\omega-\omega_0)^2}{\Gamma^2} + \frac{1}{4}\right]}\left[\frac{1-q^2}{4} - \frac{\omega - 2\omega_0}{\left(4\frac{\omega_0^2}{\Gamma^2}+1\right)\Gamma}\left(\frac{\omega_0}{\Gamma}(q^2-1)+q\right)\right]. \quad (7)$$

Using formulas (1), (3)-(7) one can calculate the scattering cross section on Fano resonance.

For example radiation scattering cross section on He atom in the vicinity of the first Fano resonance is shown in Fig. 1.

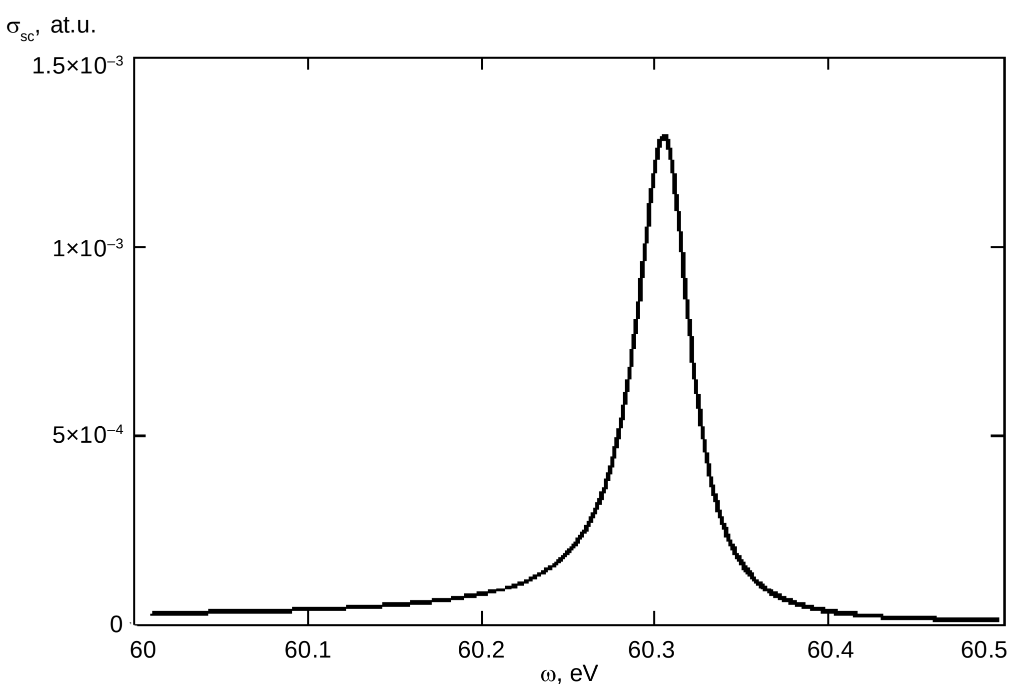

Figure 1: Photon scattering cross section on He atom in the vicinity of the first Fano resonance

From this figure slight asymmetry can be seen in spectral shape of scattering cross section.

We consider the scattering of USP with Gaussian envelope. Fourier transform of electric field strength in this pulse approximately equal to:

$$E(\omega',\omega,\tau)\cong\sqrt{\frac{\pi}{2}}\ E_0\ \tau\ \exp\left(-(\omega-\omega')^2\ \tau^2/2\right) \tag{8}$$

here E_0 is the amplitude of the electric field strength in the pulse, τ is pulse duration, ω is carrier frequency of the pulse, ω' is current frequency.

For universal description of the scattering it is worth to use dimensionless variables defined by the equalities:

$$w'=\frac{\omega'}{\Gamma},\ w=\frac{\omega}{\Gamma},\ w_0=\frac{\omega_0}{\Gamma},\ \alpha=\Gamma\tau. \tag{9}$$

Substituting formulas (3), (8) and (9) we obtain the following expression for total scattering probability in terms of dimensionless variables:

$$W(\alpha,w,w_0,q)=\frac{\alpha^2\ \Gamma^2\ E_0^2}{3\ c^3\ \hbar}\int_0^\infty w'^3\ \left|\beta(w',w_0,q)\right|^2\ \exp\left(-(w-w')^2\ \alpha^2\right)\ dw'. \tag{10}$$

Here dynamical polarizability can be calculated using eqs. (1), (4), (7).

The results of scattering probability calculations are presented in Fig. 2, 3 for the case of Fano resonance associated with the lowest autoionization state of He atom and for $E_0 = 1$ at.u.

One can see from Fig. 2 that scattering probability dependence W upon pulse duration t has non-linear character and strongly depends upon carrier frequency of the pulse.

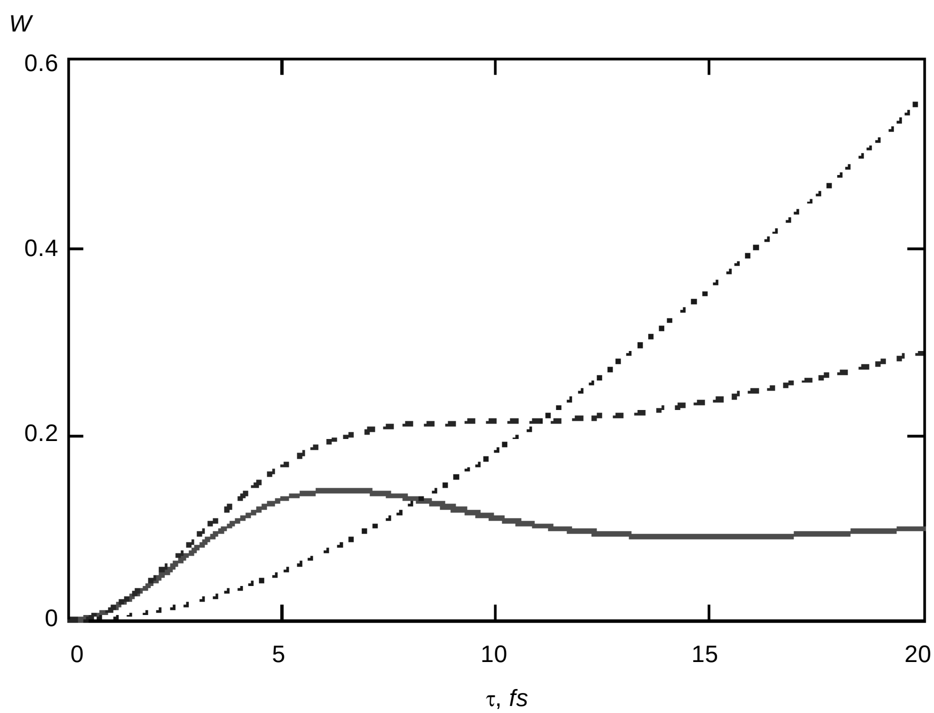

Figure 2: Scattering probability of USP on He atom versus pulse duration for various carrier frequencies: solid line – ω=60.42 eV, dotted line – $\omega = \omega_0$ = 60.3 eV (multiplied by factor 0.2), dashed line – ω = 60.19 eV

In the case of resonant carrier frequency ($\omega = \omega_0$) the function $W(\tau)$ monotonically increases firstly quadratically and then linearly with increase of pulse duration. If $\omega \neq \omega_0$ function $W(\tau)$ becomes nonmonotonic and for sufficiently large frequency detuning from Fano resonance there appears a maximum in the considered dependence.

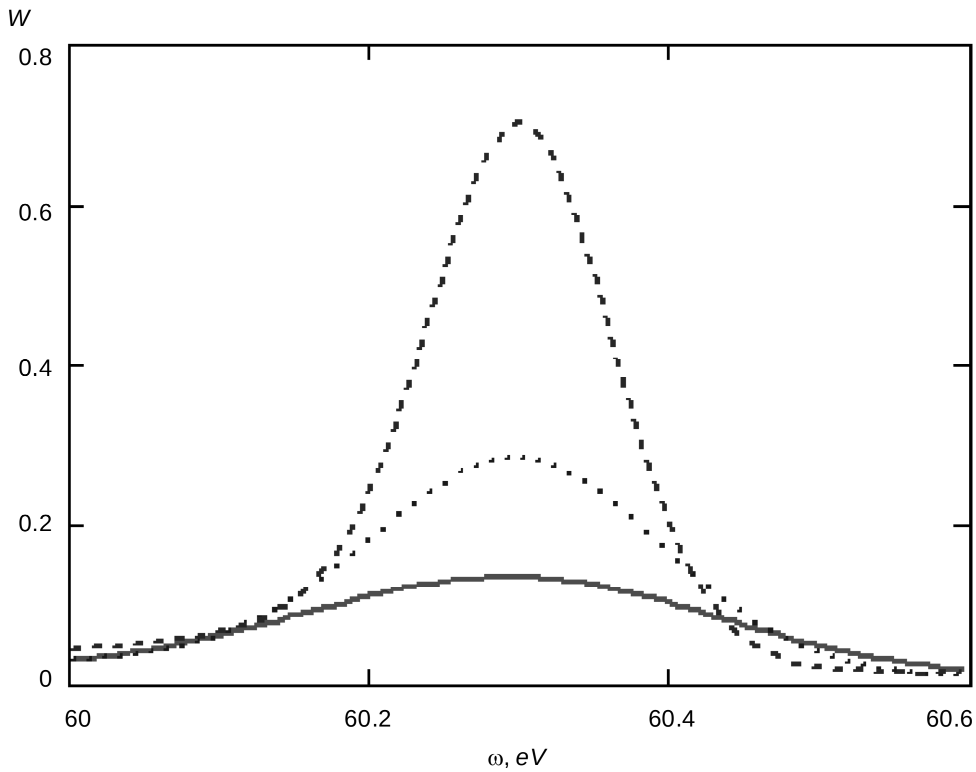

Figure 3: Spectrum of USP scattering probability on He atom for different pulse durations: solid line – τ = 3.44 fs, dotted line – τ = 5.16 fs, dashed line – τ = 8.6 fs

Spectrum of USP scattering probability becomes wider and lower in amplitude with the decrease of pulse duration while in the long pulse limit probability dependence upon carrier frequency has the same shape as scattering cross section (compare Fig. 3 and Fig. 1).

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