Coherent intense laser pulses lead to interference in the time domain: Dynamic Interference of Electron Waves

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Bound-Continuum Transitions

For ATI of model anions by optical lasers:

K. Toyota, O.I. Tolstikhin, T. Morishita, S. Watanabe,
Phys. Rev. A **76**, 043418 (2007); Phys. Rev. A **78**, 033432 (2008).

For PI of atoms by high-frequency pulses:

Ph.V. Demekhin and L.S. Cederbaum, Phys. Rev. Lett. **108**, 253001 (2012).

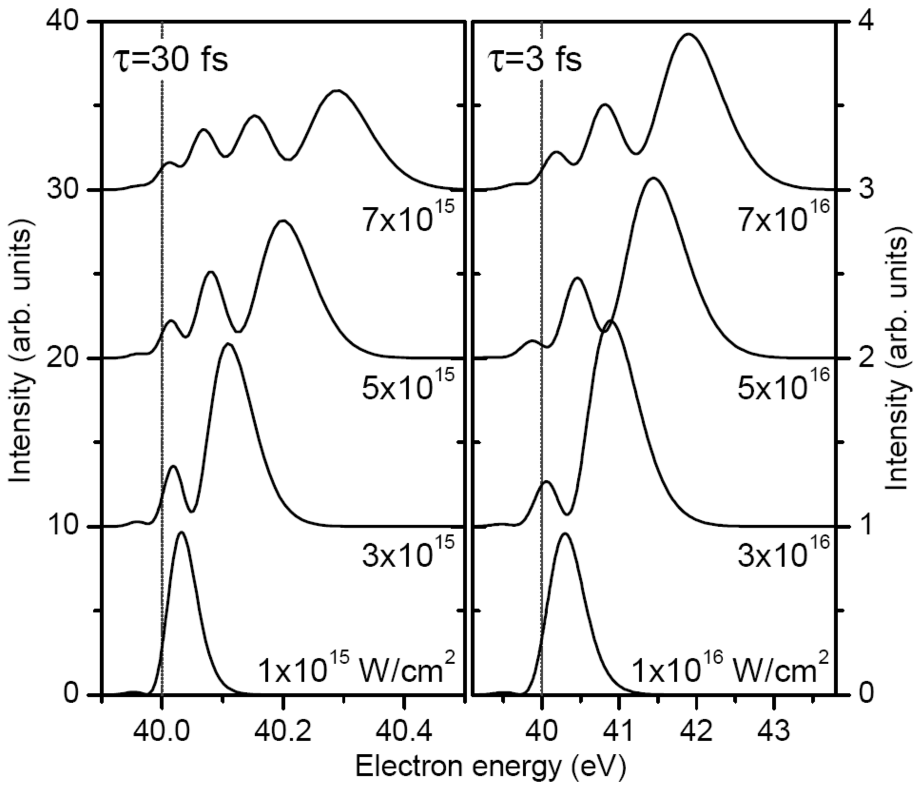
Exact photoelectron spectrum of the H atom

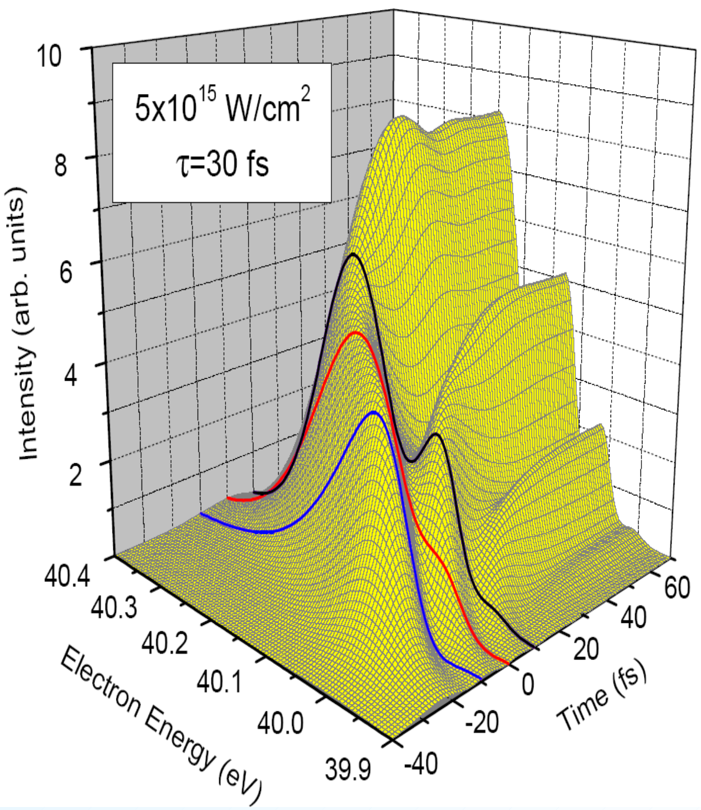
Ansatz for the total WF:

$$\Psi(t) = \sum_{even} a_e(t)|even\rangle + \sum_{odd} a_o(t)|odd\rangle.$$

$$i\dot{a}_e(t) = E_e a_e(t) + \sum_{odd} \left(\frac{\mathcal{E}_0}{2} (d_e^o)^\dagger\right) g(t) \left(e^{i\omega t} + e^{-i\omega t}\right) a_o(t)$$

$$i\dot{a}_o(t) = E_o a_o(t) + \sum_{even} \left(\frac{\mathcal{E}_0}{2} d_e^o\right) g(t) \left(e^{i\omega t} + e^{-i\omega t}\right) a_e(t)$$





Local approximation

Ansatz for the total WF (essential states):

$$\Psi(t) = a_I(t)|I\rangle + \int d\varepsilon \, a_\varepsilon(t)|F\varepsilon\rangle e^{-i\omega t},$$

$$i\dot{a}_I(t) = \int d\varepsilon \, \left\{\tfrac{1}{2}d^\dagger_\varepsilon \mathcal{E}_0\right\} g(t)\, a_\varepsilon(t),$$

$$i\dot{a}_\varepsilon(t) = \left\{\tfrac{1}{2}d_\varepsilon \mathcal{E}_0\right\} g(t)\, a_I(t) + (IP + \varepsilon - \omega)\, a_\varepsilon(t).$$

Ground state solution in the local approximation:

$$i\dot{a}_I(t) = \left(\Delta - \tfrac{i}{2}\Gamma\right) g^2(t)\, a_I(t).$$

$$a_I(t) = e^{(-i\Delta - \Gamma/2)J(t)}$$

$$J(t) = \int_{-\infty}^{t} g^2(t')dt'$$

AC Stark Shift and ionization rate:

$$\Delta = -\mathcal{P}\int d\varepsilon \left|\frac{d_\varepsilon \mathcal{E}_0}{2}\right|^2 \left(\frac{1}{IP + \varepsilon - \omega} + \frac{1}{IP + \varepsilon + \omega}\right)$$

$$\Gamma = 2\pi \, \left|\tfrac{1}{2}d_{\varepsilon_0}\mathcal{E}_0\right|^2$$

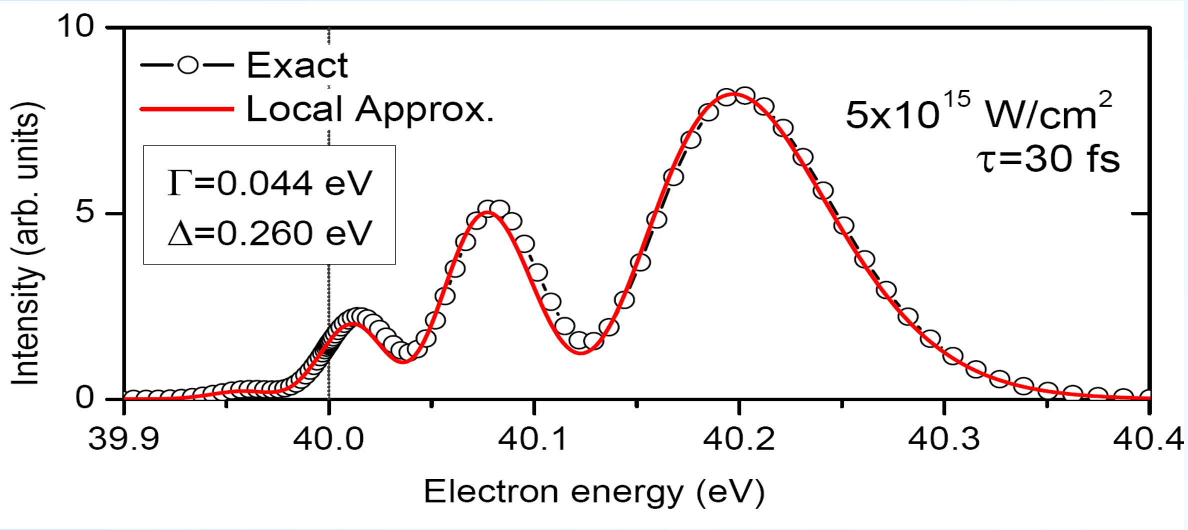
Local approximation

Population of the final continuum states:

$$a_\varepsilon(t) = -i\ \{\tfrac{1}{2} d_\varepsilon \mathcal{E}_0\}\ e^{-i\delta t} \int_{-\infty}^{t} g(t')\, a_I(t')\, e^{i\delta t'}\, dt',$$

Final photoelectron spectrum:

$$\sigma(\varepsilon) = \left| \frac{d_\varepsilon \mathcal{E}_0}{2} \int_{-\infty}^{+\infty} g(t)\, e^{-\Gamma/2 J(t)} e^{i[\delta t - \Delta J(t)]} dt \right|^2 .$$



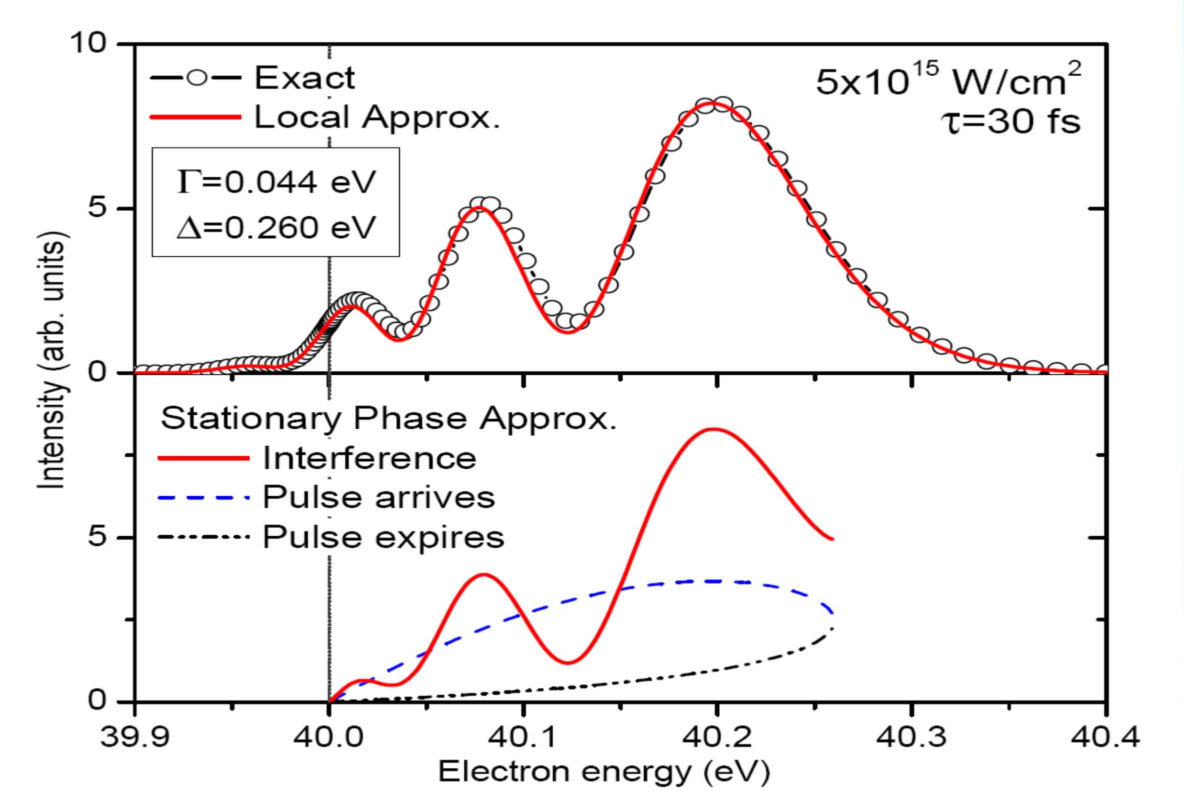
Stationary phase approximation

Stationary phase condition and the spectrum:

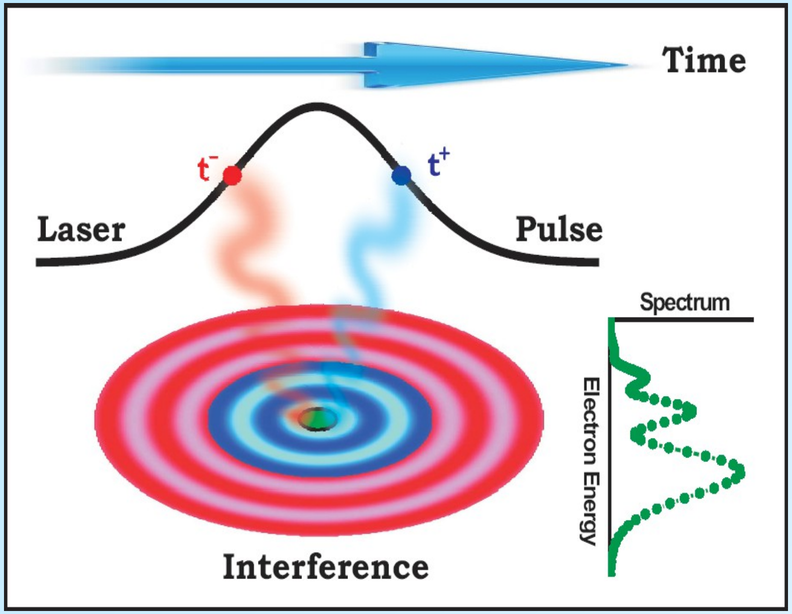
$$\Phi(t) = \delta t - \Delta J(t)$$

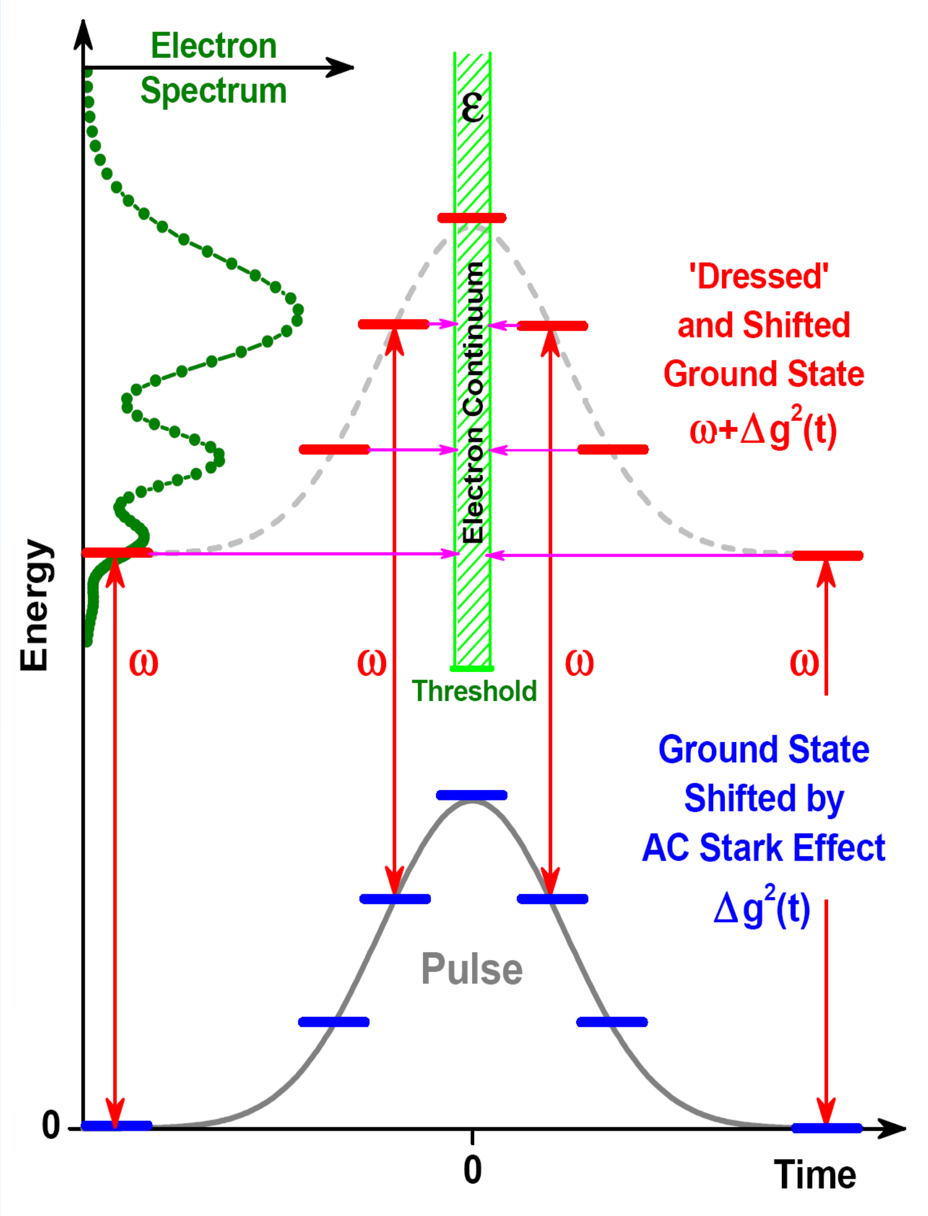
$$\dot{\Phi}(t_s) = \delta - \Delta g^2(t_s) = 0.$$

$$\sigma(\varepsilon) = \left| \frac{d_\varepsilon \mathcal{E}_0}{2} \sum_{t_s = \pm t_1(\varepsilon)} g(t_s) e^{-\Gamma/2 J(t_s)} e^{i\left[\Phi(t_s) \pm \frac{\pi}{4}\right]} \right|^2$$



Dynamic Interference





Physical meaning of the stationary phase:

$$\omega + \Delta g^2(t) = IP + \varepsilon$$

Bound-Bound Transitions

For autoionization and resonant MPI by optical lasers:

K. Rzazewski, Phys Rev A 28, 2565 (1983).

D. Rogus and M. Lewenstein, J. Phys. B 19, 3051 (1986).

C. Meier and V. Engel Phys Rev Lett 73, 3207 (1994).

For resonant TPI and RA effect by high-frequency pulses:

Ph.V. Demekhin and L.S. Cederbaum, submitted (2012) **arXiv:1208.0507v2**

Dynamic interference in the two-photon ionization of H

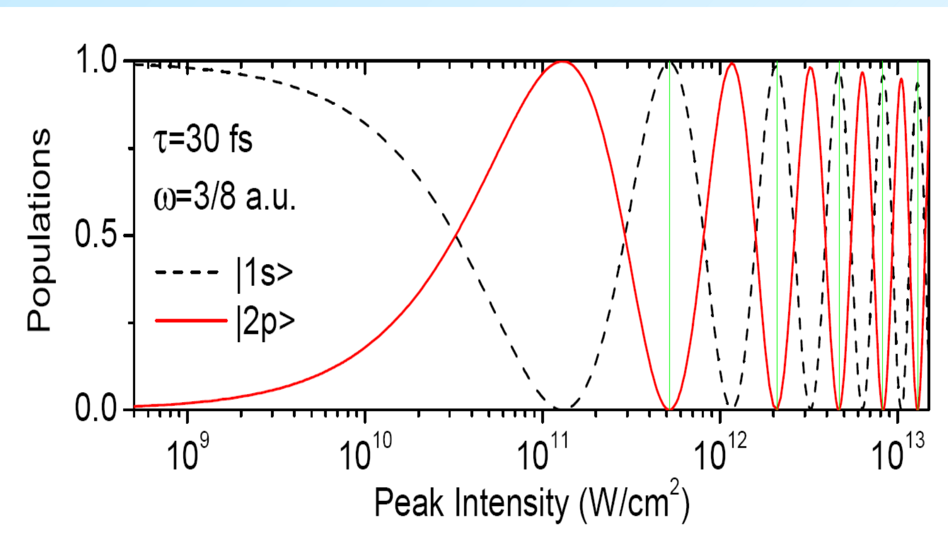
Ansatz for the total WF:

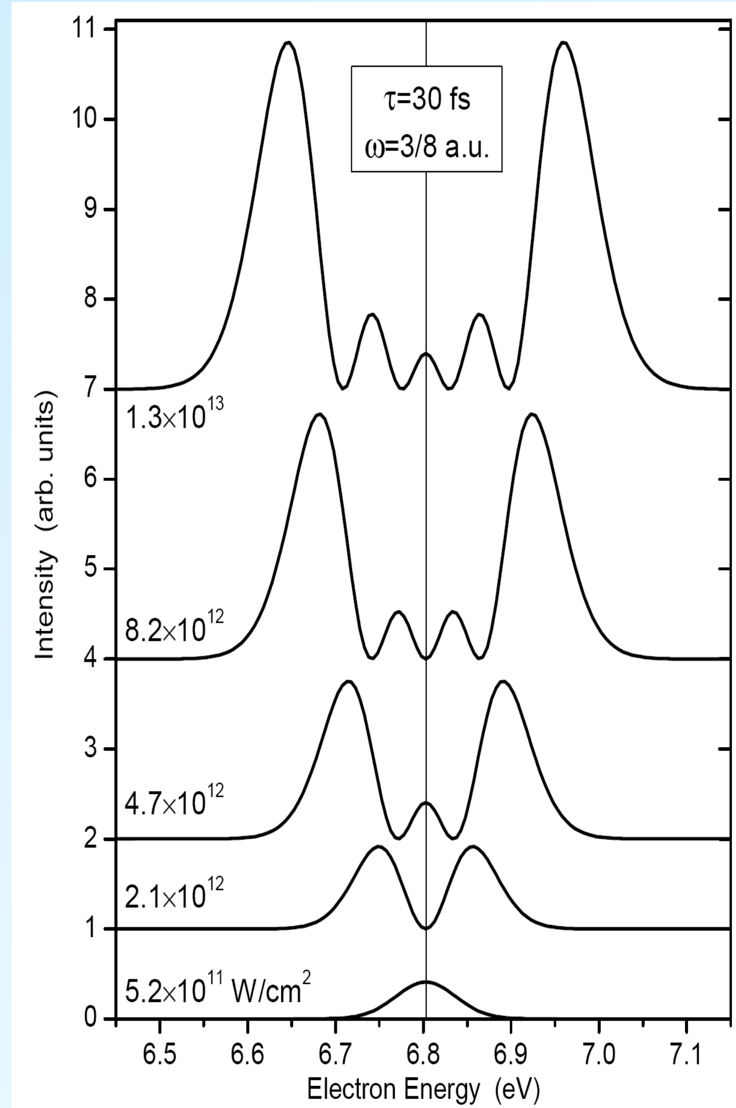
$$\Psi(t) = a_I(t)|I\rangle + a_R(t)e^{-i\omega t}|R\rangle + \int a_\varepsilon(t)e^{-2i\omega t}|F\varepsilon\rangle d\varepsilon.$$

$$i\dot{a}_I(t) = \frac{D^\dagger \mathcal{E}_0}{2}\, g(t)\, a_R(t), \tag{2a}$$

$$i\dot{a}_R(t) = \frac{D\mathcal{E}_0}{2}\, g(t)\, a_I(t) + (E_R - \tfrac{i}{2}\Gamma g^2(t) - \omega)a_R(t), \tag{2b}$$

$$i\dot{a}_\varepsilon(t) = \frac{d\mathcal{E}_0}{2}\, g(t)\, a_R(t) + (IP + \varepsilon - 2\omega)\, a_\varepsilon(t). \tag{2c}$$





Dynamical coupling of resonances

2x2 Hamiltonian

$$\mathbf{H}(t) = \begin{vmatrix} 0 & \Delta^\dagger g(t) \\ \Delta g(t) & -\frac{i}{2}\Gamma g^2(t) \end{vmatrix}$$

$$E_+(t) \simeq +\Delta g(t) - \frac{i}{4}\Gamma g^2(t), \quad |+\rangle \simeq \frac{|I\rangle}{\sqrt{2}} + \frac{|R\rangle}{\sqrt{2}},$$
$$E_-(t) \simeq -\Delta g(t) - \frac{i}{4}\Gamma g^2(t), \quad |-\rangle \simeq \frac{|I\rangle}{\sqrt{2}} - \frac{|R\rangle}{\sqrt{2}}.$$

$$i\dot{a}_-(t) = \left[-\Delta g(t) - \tfrac{i}{4}\Gamma g^2(t)\right] a_-(t),$$

$$i\dot{a}_+(t) = \left[+\Delta g(t) - \tfrac{i}{4}\Gamma g^2(t)\right] a_+(t),$$

$$i\dot{a}_\varepsilon(t) = -\frac{d\mathcal{E}_0}{2\sqrt{2}}\, g(t)\, a_-(t) + \frac{d\mathcal{E}_0}{2\sqrt{2}}\, g(t)\, a_+(t) + (IP + \varepsilon - 2\omega)\, a_\varepsilon(t).$$

Decoupled resonances scenario:

$$a_+(t) = \frac{1}{\sqrt{2}}\, e^{[-i\Delta F(t) - \Gamma/4\, J(t)]},$$

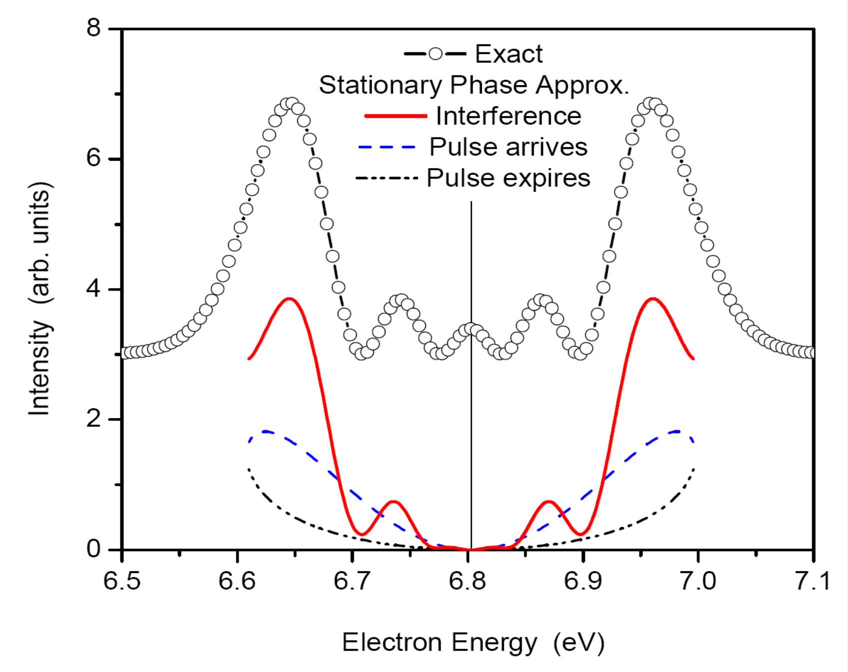
$$a_-(t) = \frac{1}{\sqrt{2}}\, e^{[+i\Delta F(t) - \Gamma/4\, J(t)]},$$

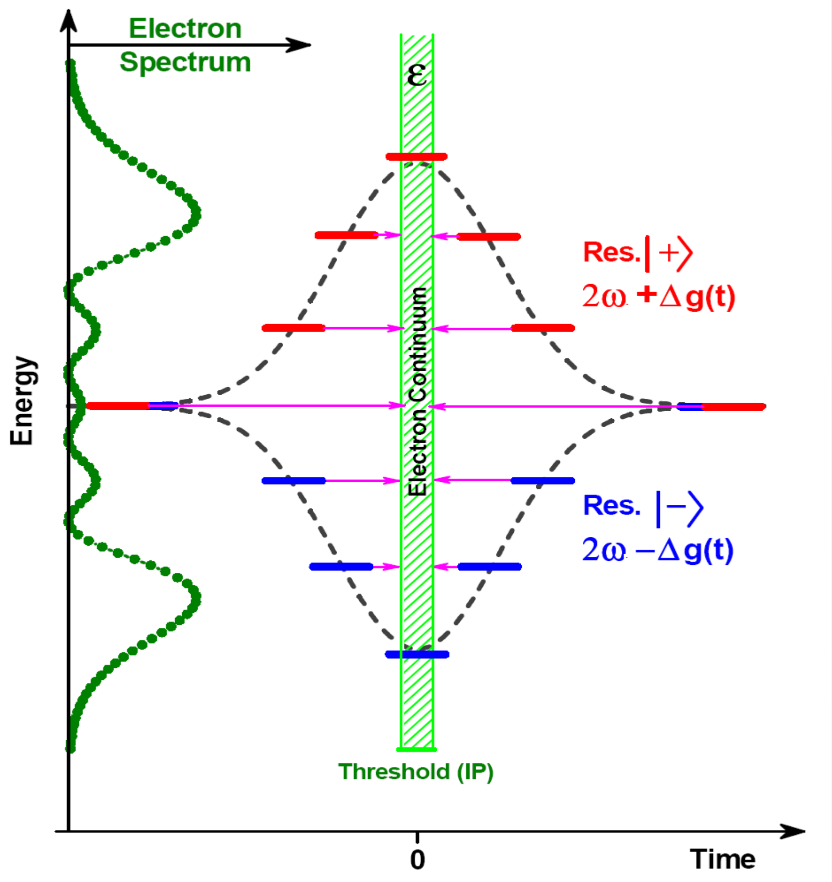
Spectrum:

$$\sigma(\varepsilon) = \left| \frac{d\mathcal{E}_0}{4} \int_{-\infty}^{\infty} g(t)\, e^{-\Gamma/4\, J(t)} \left\{ -e^{i[\delta t + \Delta F(t)]} + e^{i[\delta t - \Delta F(t)]} \right\} dt \right|^2 .$$

$$F(t) = \int_{-\infty}^{t} g(t')dt' \ \text{ and } \ J(t) = \int_{-\infty}^{t} g^2(t')dt'.$$

Dynamic interference in the two-photon ionization





Physical meaning

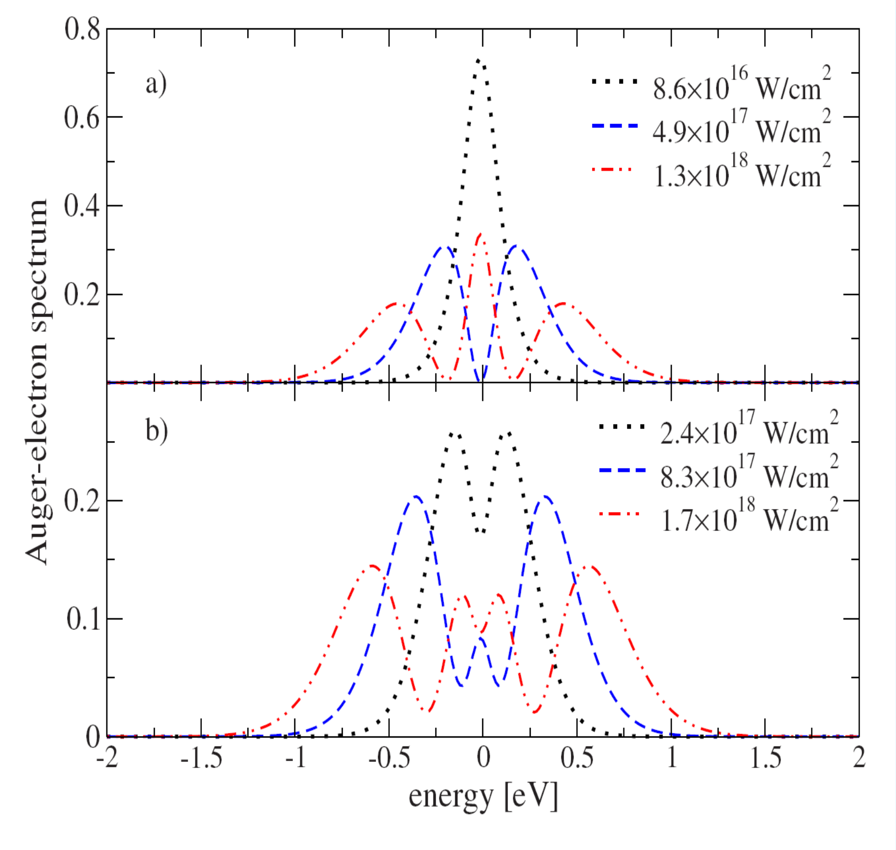
$$\varepsilon = 2\omega - IP \mp \Delta g(t_s)$$

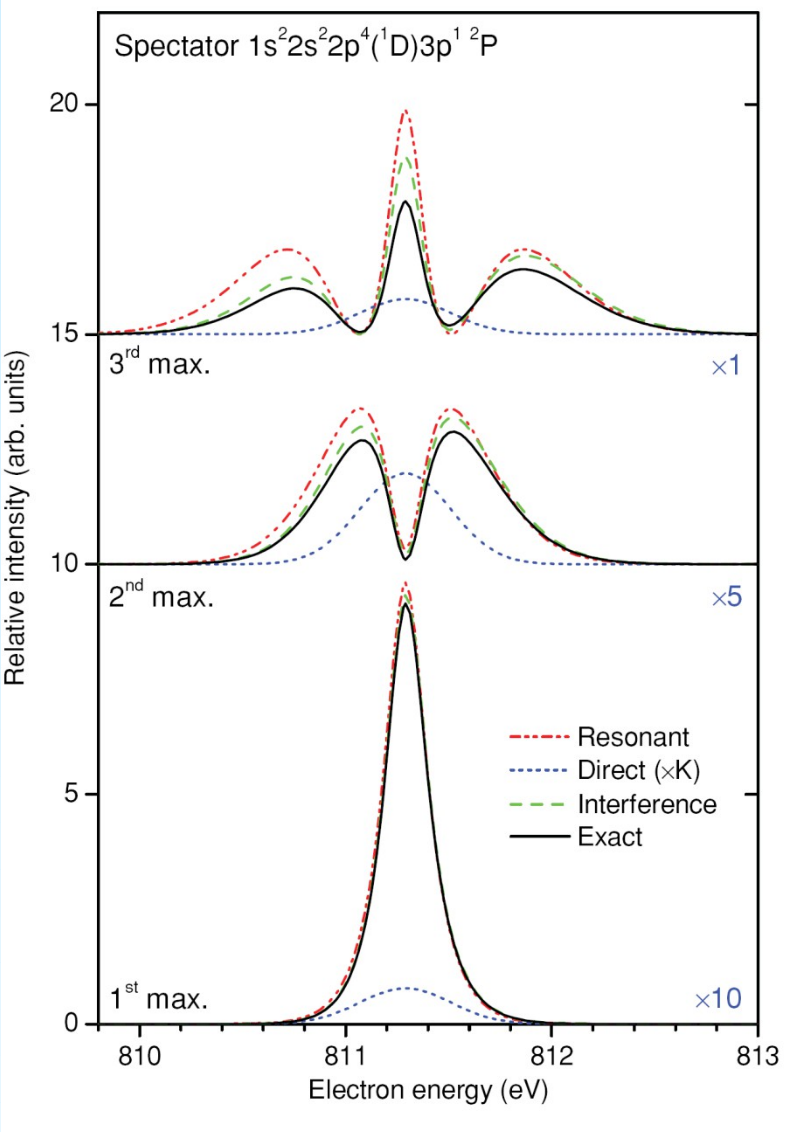
$$\sigma(\varepsilon) \simeq \left| \frac{d\mathcal{E}_0}{4} \sum_{t_s=\pm t_1(\varepsilon)} g(t_s)\, e^{-\Gamma/4J(t_s)} \left\{ -e^{i\left[\Phi_+(t_s)\mp\frac{\pi}{4}\right]} + e^{i\left[\Phi_-(t_s)\pm\frac{\pi}{4}\right]} \right\} \right|^2 .$$

Dynamic interference in the resonant Auger decay

N. Rohringer and R. Santra

Ph. V. Demekhin and L. S. Cederbaum





Summary

- Dynamic interference is a general consequence of the finite nature of laser pulses, and it is fundamental to the spectroscopy of strong laser fields. Whenever the field-induced couplings between electronic states of a system possess the time dependence $g(t)$ provided by the pulse, the phenomenon of dynamic interference takes place.

- Where it can be seen:

Single-photon ionization (due to AC Stark effect)

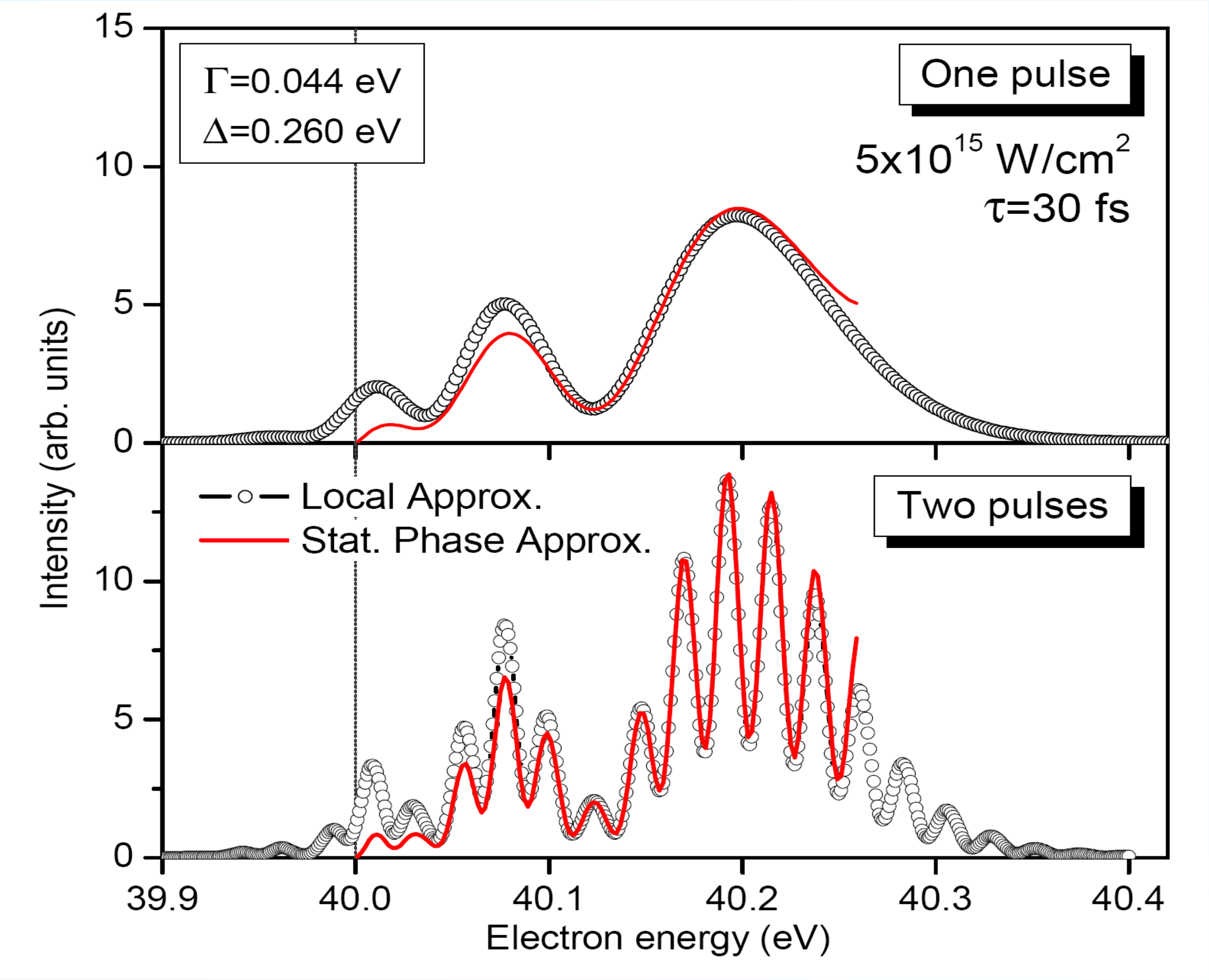
Two-photon ionization (due to resonant coupling)

Resonant auger decay (due to resonant coupling)

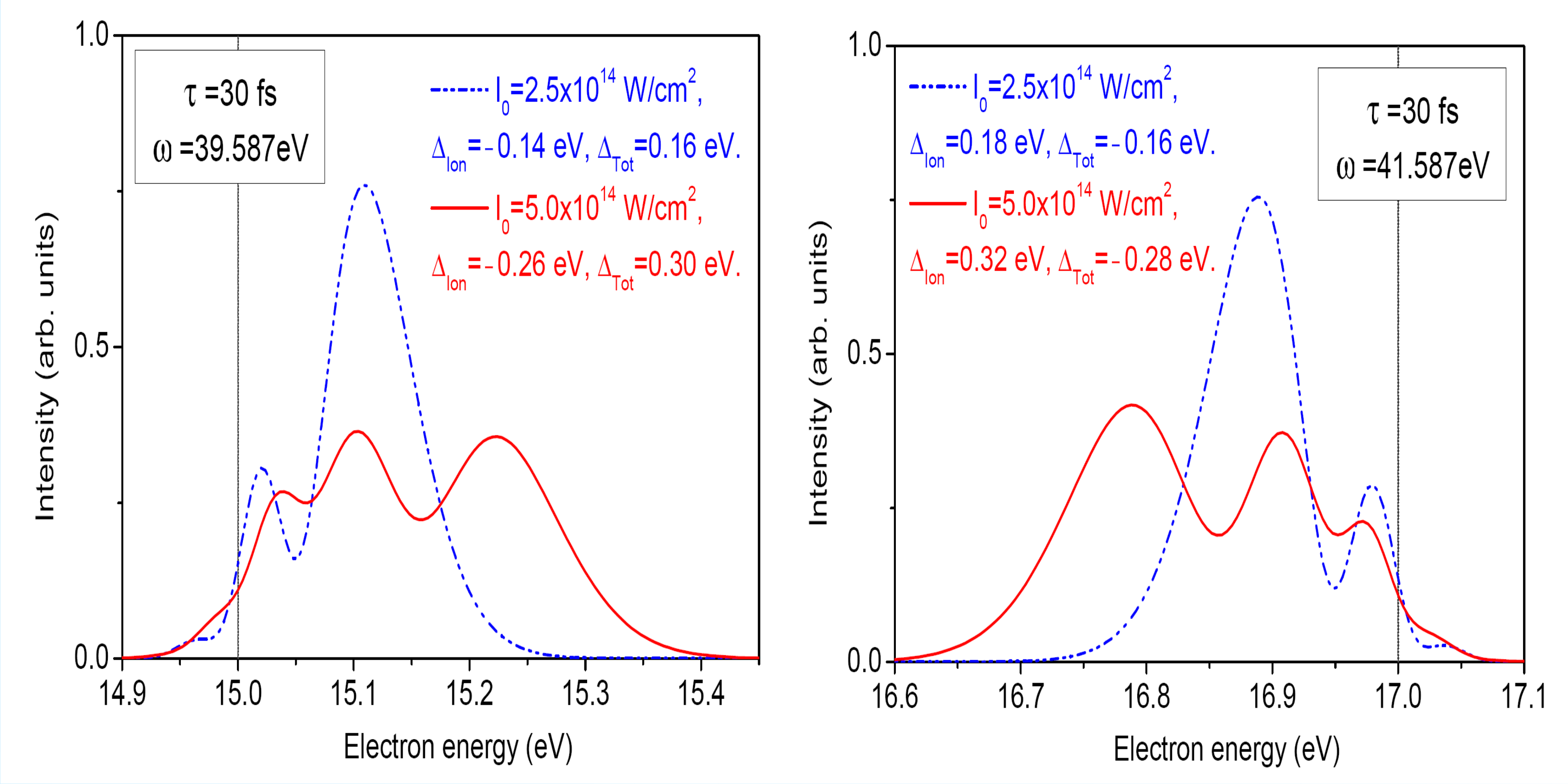
X-ray photoemission (resonant coupling or AC Stark effect)

Extra material

Controllability of the dynamic interference



Dynamic Interference in He



Total AC Stark shift:

$$\Delta_{Tot} = \Delta - \Delta_{Ion}$$