Ионизация атомов при совместном действии ультракоротких рентгеновского и инфракрасного лазерных импульсов

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DESY, FLASH and XFEL

XFEL проект


Schleswig-Holstein
Hamburg
Schenefeld
Osdorfer Born
DESY-Bahrenfeld
0 m
500 m

XFEL versus FLASH

	European XFEL	FLASH	
Abbreviation for	European X-ray Free-Electron Laser	Free-Electron Laser in Hamburg	
Start of commissioning	2014	2004	
Length of the accelerator	1.7 kilometres	0.15 kilometres	x11
Length of the facility	3.4 kilometres	0.3 kilometres	x11
Number of accelerator modules	100	7	x14
Maximum electron energy	17.5 billion electron volts (17.5 GeV)	1 billion electron volts (1 GeV)	17.5
Minimum wavelength of the laser light	0.1 nanometre (of the order of an atom)	4.5 nanometres (of the order of a molecule)	x1/45
Number of undulators (magnet structures for light generation)	5	1	
Number of experiment stations	10 completely instrumented	5	x2

XFEL versus LCLS and SPring8

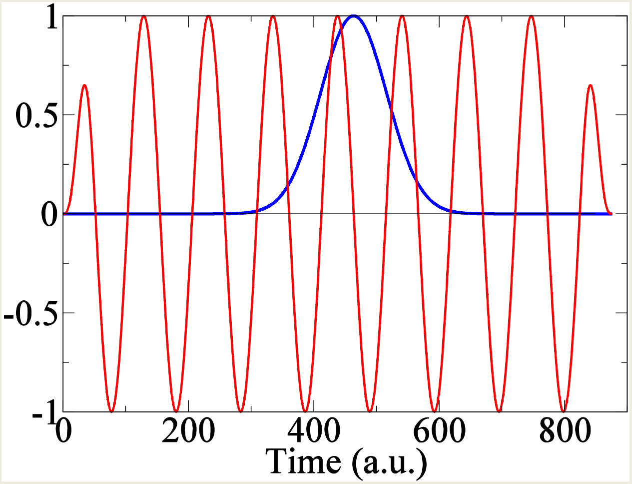
	LCLS	SACLA	European XFEL
Abbreviation for	Linac Coherent Light Source	SPring-8 Angstrom Compact Free Electron Laser	European X-Ray Free-Electron Laser
Location	California, USA	Japan	Germany
Start of commissioning	2009	2011	2014
Accelerator technology	normal conducting	normal conducting	superconducting
Number of light flashes per second	120	60	27 000

Two-colour short-pulse photoionization of atoms

Infrared (IR) laser pulse:

ω= 1.66 eV (800 nm), T_L = 2.5 fs

I = $10^{12} - 10^{14}$ W/cm^2



XUV pulse ω= 70 – 130 eV

The main parameters: τ_L - duration of the IR pulse

τ_{XUV} - duration of the XUV pulse

T_L - period of the IR pulse

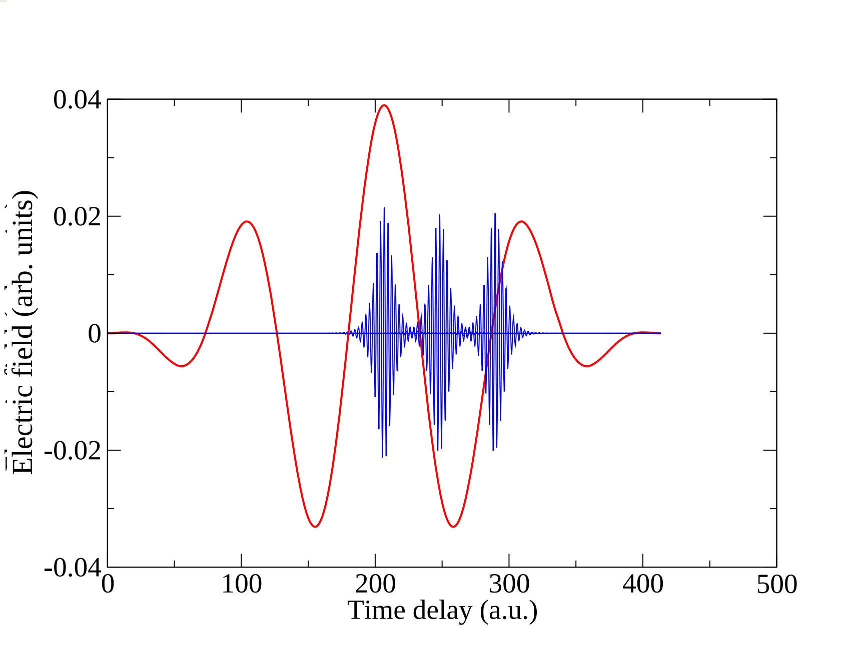
Two limiting cases:

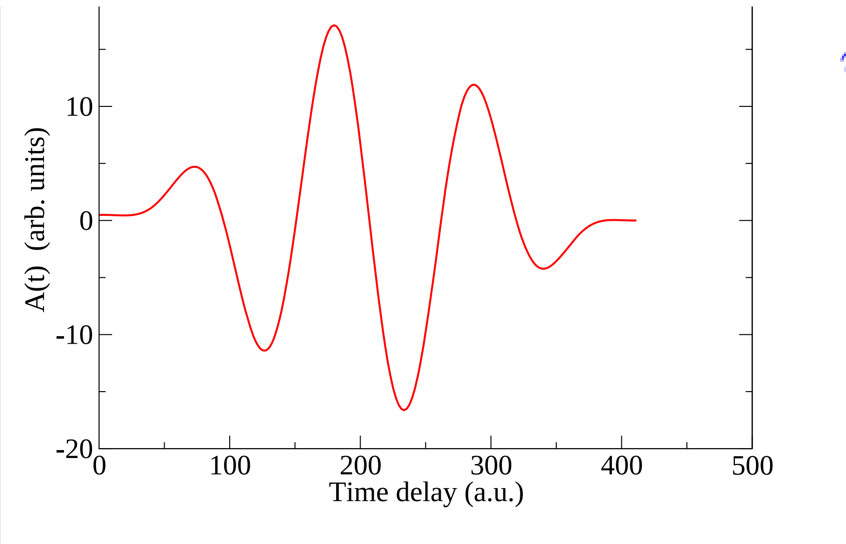
A: $\tau_{XUV} \ll T_L$ Streaking

B: $\tau_L > \tau_{XUV} \gg T_L$ Sidebands

Case A: $\tau_{XUV} \ll T_L$, streaking experiment

(Qualitative explanation)





Laser field: strong, 10^{13} -10^{14} W/cm^2,

few-cycle, τ_L~ 5 fs, E_L = 1.6 eV (800 nm)

XUV pulse: weak, τ_X~300 as, E_X=90eV

Modification of electron spectra in a strong IR field:

$$v_z(t \rightarrow \infty) = v_{z0} - \frac{e}{m} \int_{t_i}^{\infty} E_L(t) dt$$

$$= v_{z0} - \frac{e}{m} A(t_i)$$

a) Energy shift

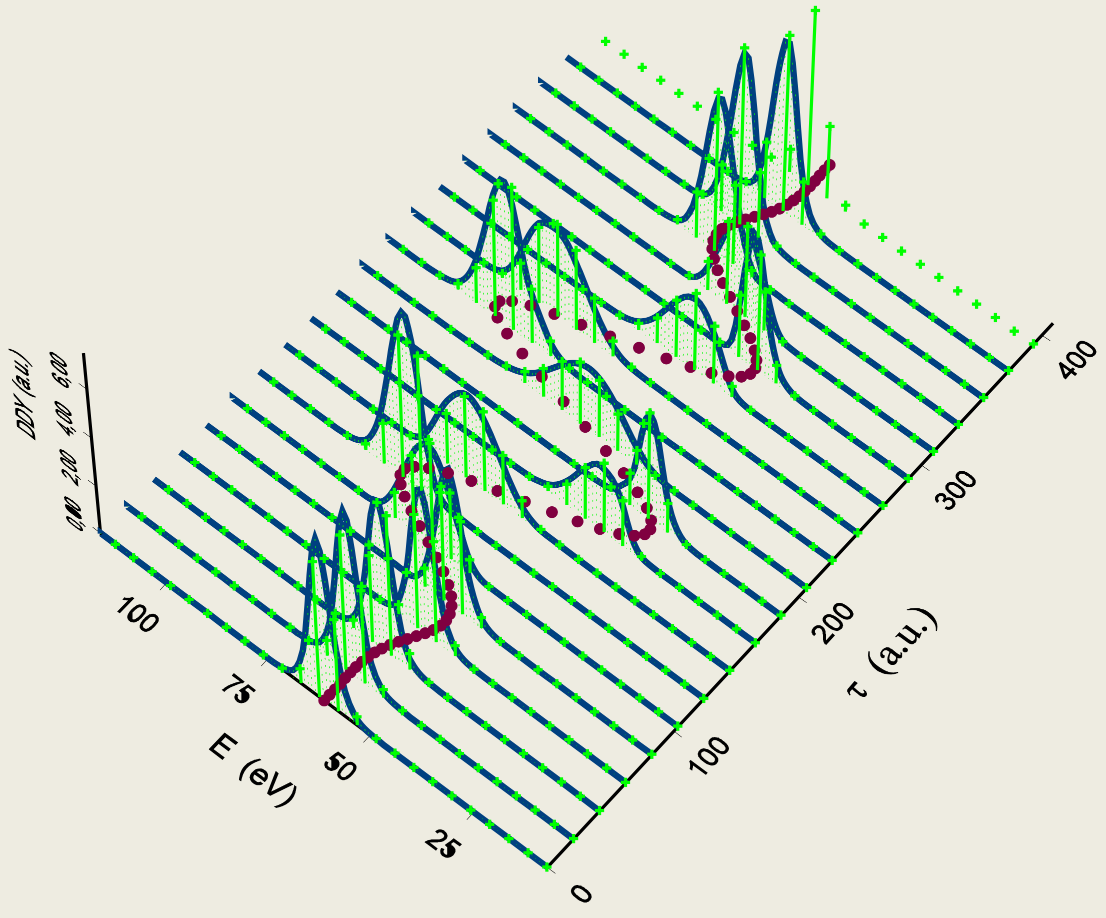
b) Energy spread

Theoretical results: Ar (3s) photoionization

Example: A.Kazansky and N. Kabachnik J. Phys. B 40, 2163 (2007)

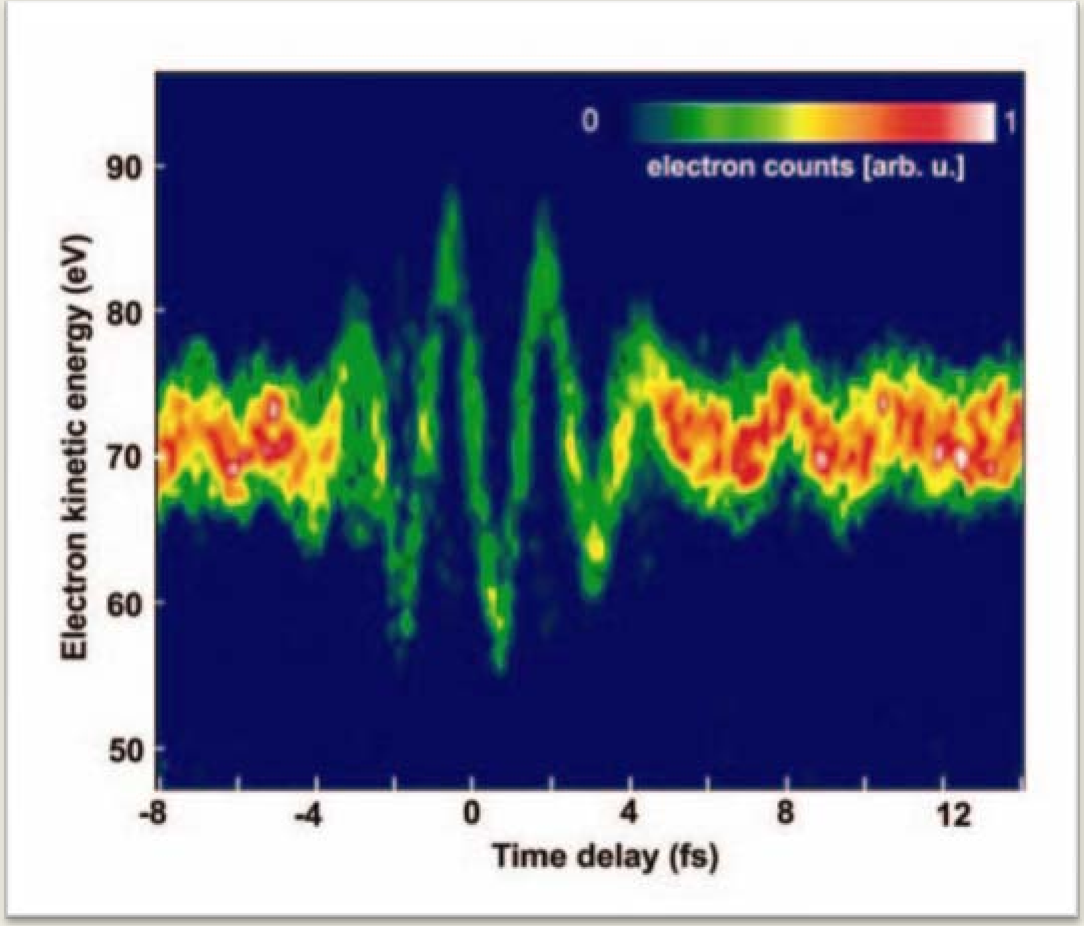
Ar (3s); I= 28.6 eV IR: τ_L= 5 fs, λ = 800 nm, W = 10^{13} W/cm^2

XUV: E_X= 90 eV , τ_X = 330 as



Experimental results: Ne(2p) photoionization

Example: M. Gouliemakis et al. Science 305, 1267, 2004



Pump: XUV, E=93 eV, T=250 as

Probe: IR 750 nm, T=5 fs

Photoelectrons are detected along the laser polarization

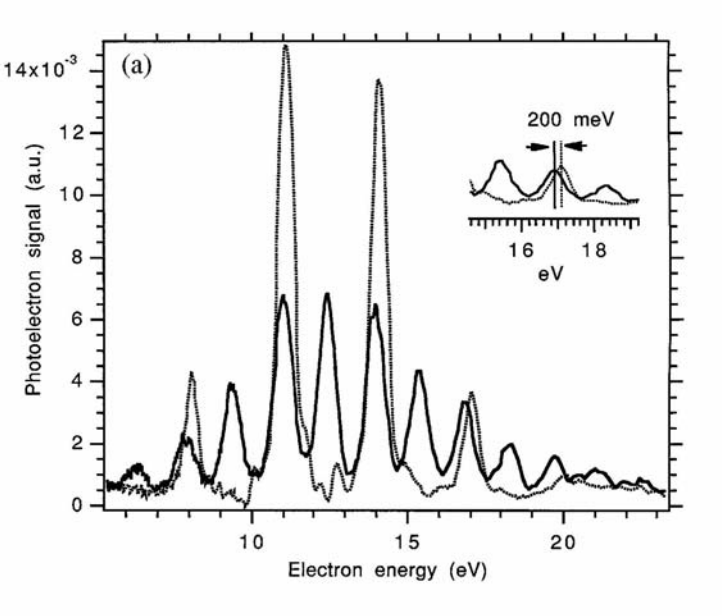
Case B: $\tau_L > \tau_{XUV} \gg T_L$, sideband formation

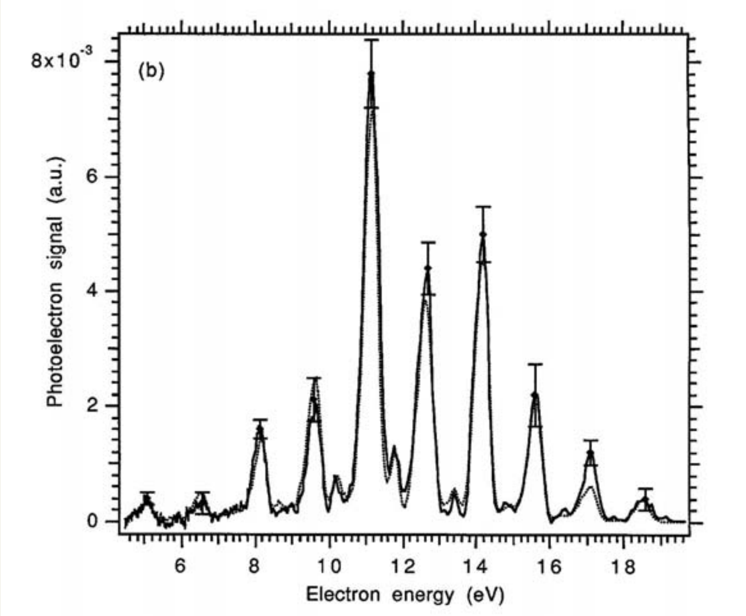
Emitted electron interacts with the laser field:

it can absorb or emit IR - photons

Experimental results: He photoionization

Example: Glover et al. PRL 76, 2468 (1996)





Theory: strong field approximation

L. Keldysh 1965

Amplitude of photoionization

$$\mathcal{A}_{\vec{k}} = -i \int_{-\infty}^{\infty} dt\, \bar{\mathcal{E}}_X(t) < \Psi_f \psi_{\vec{k}} | \hat{D} | \Psi_0 > \exp[i(E_b - \omega_X)t]$$

Electron wave function in the laser field (Volkov wave-function):

$$\psi_{\vec{k}} = \exp\left\{ i[\vec{k} - \vec{A}_L(t)]\vec{r} - i\Phi(\vec{k}, t) \right\}$$

where $\Phi(\vec{k}, t) = \frac{1}{2} \int_{-\infty}^{t} dt' \left[\vec{k} - \vec{A}_L(t') \right]^2$ Volkov phase

Approximately $\mathcal{A}_{\vec{k}} \approx -i \vec{d}_{\vec{k}} \mathcal{F}(\vec{k})$

$$\mathcal{F}(\vec{k}) = \int_{t_0}^{t_M} dt' \bar{\mathcal{E}}_X(t') \exp\left[-i \int_{t_0}^{t'} dt'' \frac{1}{2} \left([\vec{k} - \vec{A}_L(t'')]^2 - k_0^2 \right) \right]$$

$$k_0^2/2 = \omega_X - E_b$$

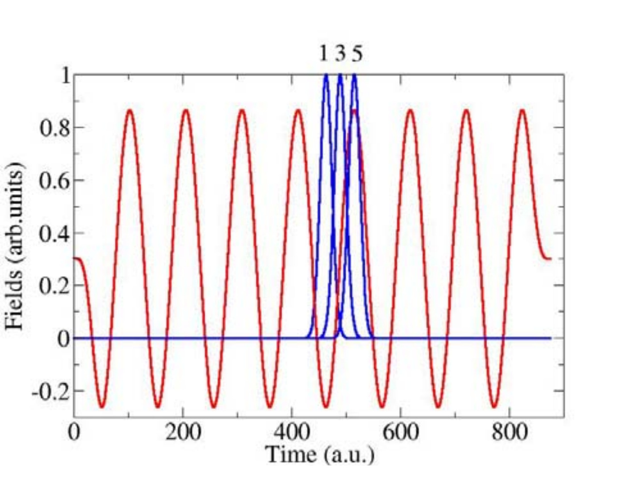
Results of calculations. Case A – streaking regime

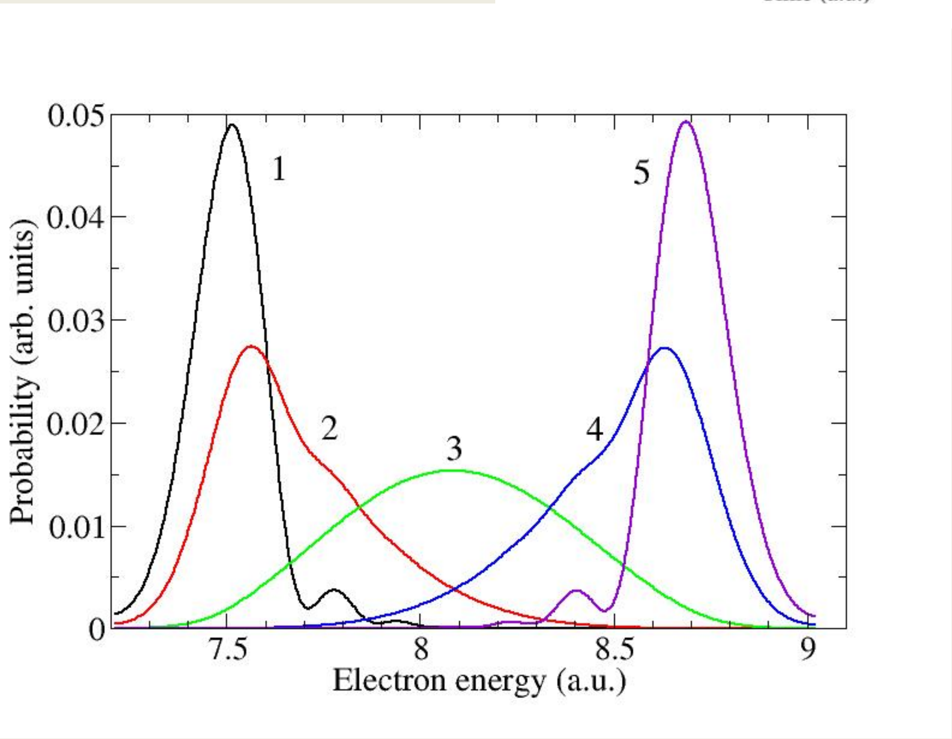
IR: I= 3.5 × 10^{12} W/cm^2

T_L = 2.5 fs (800 nm)

XUV: τ_X = 0.5 fs

E_e = 220 eV (8.1 a.u.)

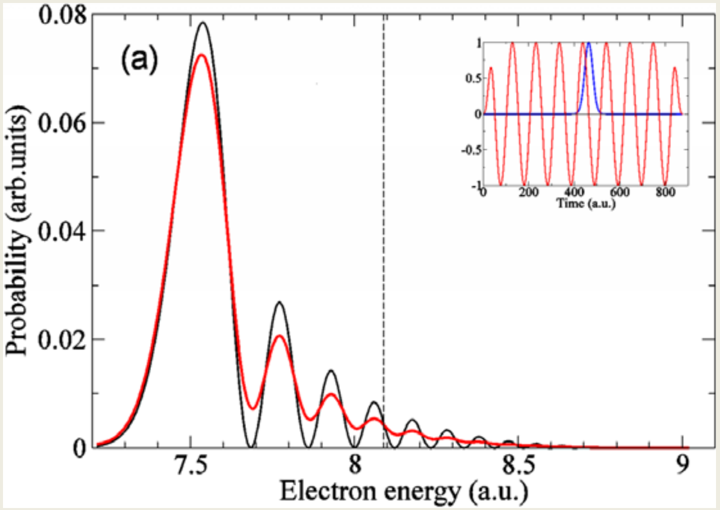




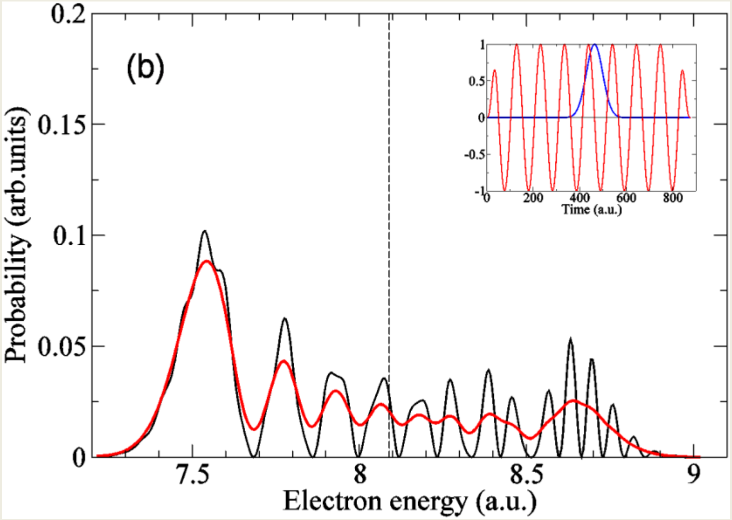
Results of calculations for different τ_X

A.K. Kazansky, I.P. Sazhina, N.M. Kabachnik, Phys.Rev. A 82, 033420, 2010

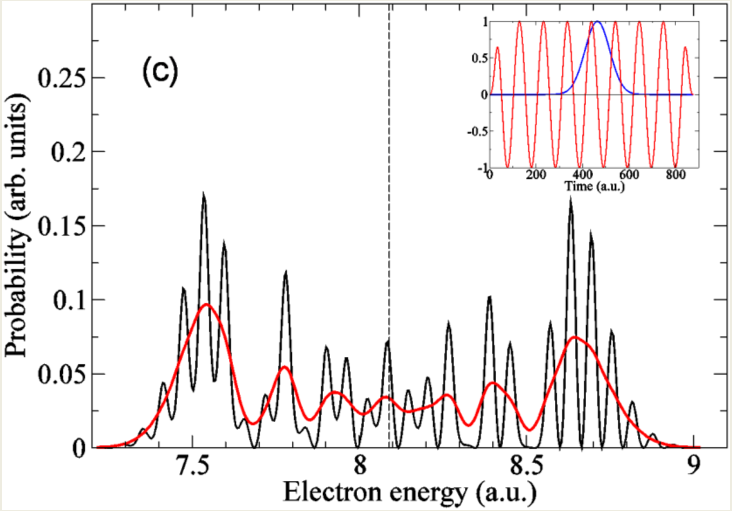
1 fs



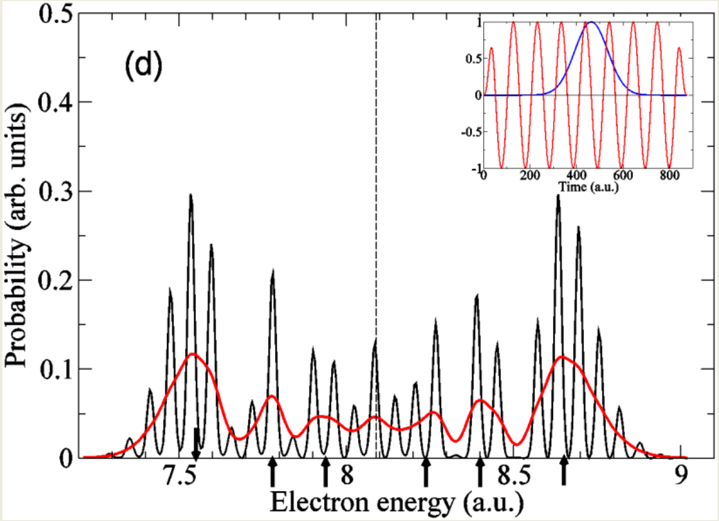
2 fs



3 fs



4 fs



Description of the gross structure

$$\mathcal{F}(k) \approx \tilde{E}(k) \frac{1-(J(k))^{N_{max}+1}}{1-J(k)}$$

$$\tilde{E}(k) = \mathcal{E}_{0X} \int_0^{T_L} dt e^{iQ(t)}$$ where $$Q(t) = \int_0^t dt' \frac{1}{2} \left([k - A_L(t')]^2 - k_0^2 \right)$$

Suppose for simplicity that $A_L(t) = \sin \omega_L t + \alpha$

Stationary phase approximation $[k - A_L(t_s)]^2 = k_0^2$

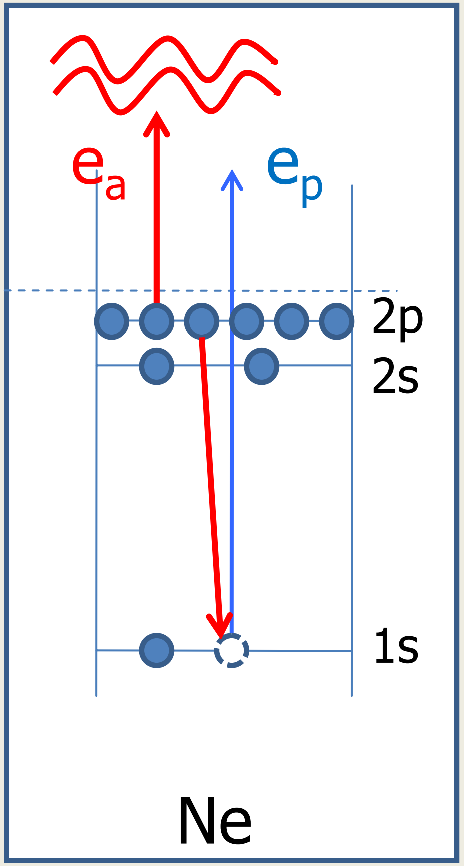
Result: $\tilde{E}(k) \sim \mathcal{E}_{0X} Ai(S)$ $\tilde{E}(k) \sim \mathcal{E}_{0X} Ai(\bar{S})$

$k > \alpha + k_0$ $k < \alpha + k_0$

$$S = \frac{\left[(k-\alpha-A_0)^2 - k_0^2\right]}{[4A_0\omega_L^2(k-\alpha-A_0)]^{1/3}} \qquad \bar{S} = \frac{\left[(k-\alpha+A_0)^2 - k_0^2\right]}{[-4A_0\omega_L^2(k-\alpha+A_0)]^{1/3}}$$

Sideband formation in laser-assisted Auger decay

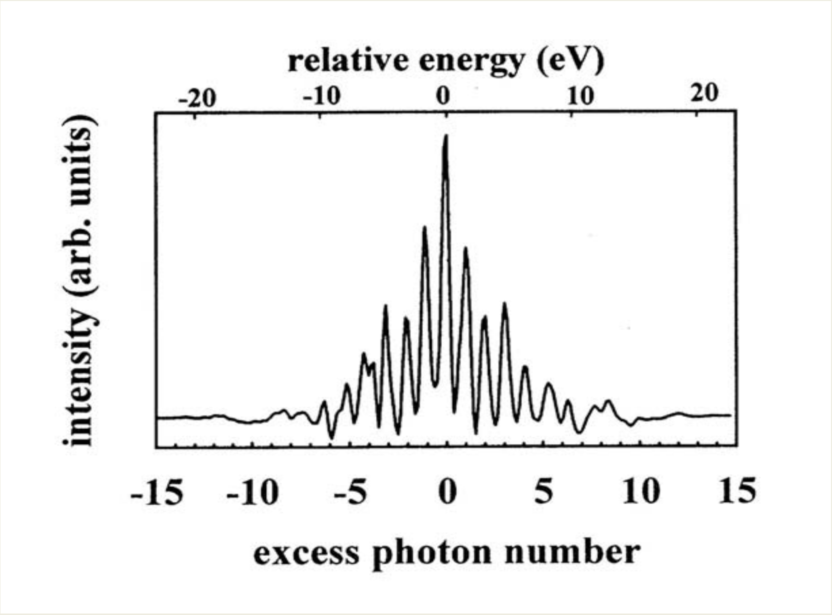
First experiment: J.M. Schins et al. PRL 73, 2180, 1994



LMM transitions in Ar

IR laser 800 nm

TOF electron spectrometer of the magnetic bottle type

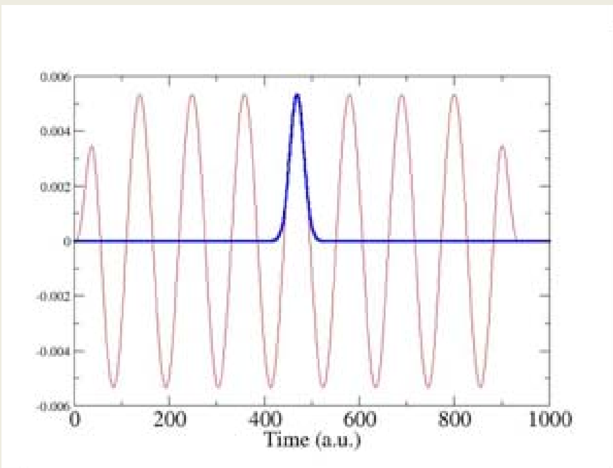


Sideband structure for Ne KLL Auger transition

A. Kazansky and N. Kabachnik J. Phys. B 43, 035601 (2010)

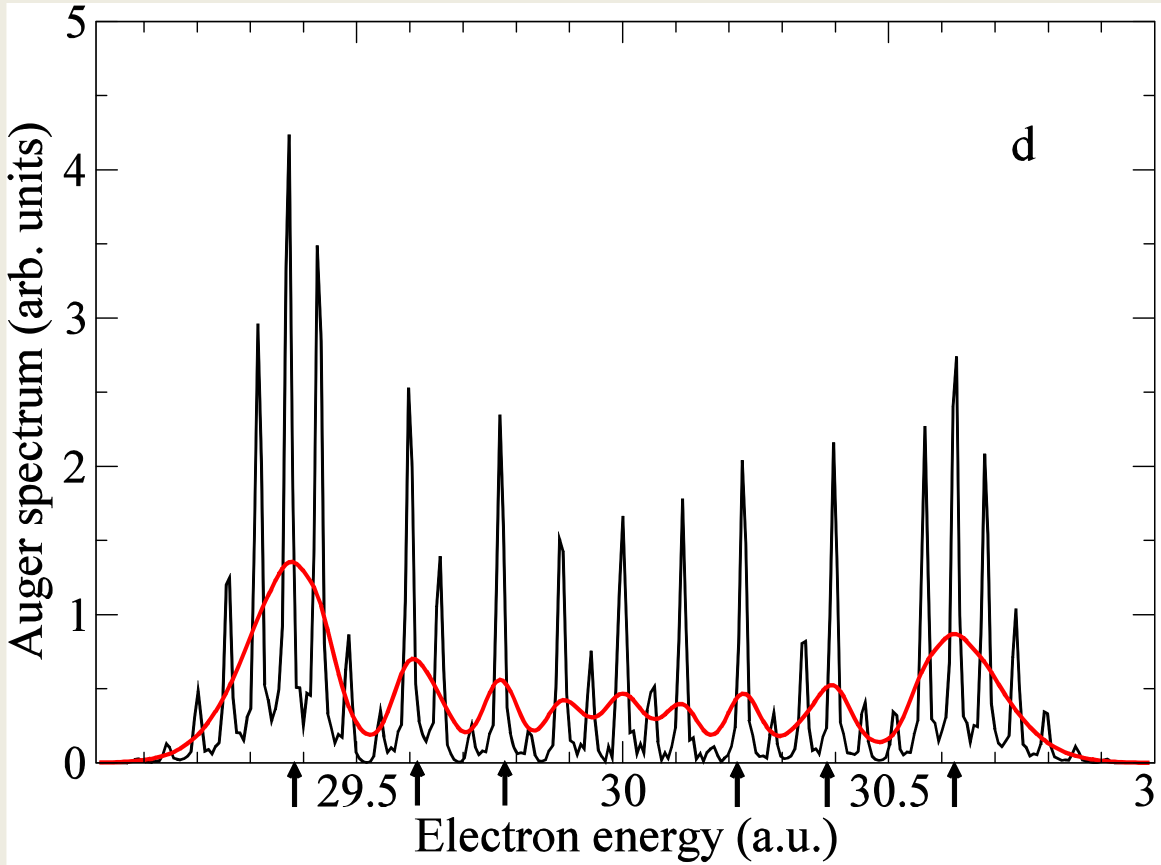
Ne (1s), KLL

E_A = 804.3 eV (30 a.u.)
τ_A = 2.4 fs (100 a.u.)

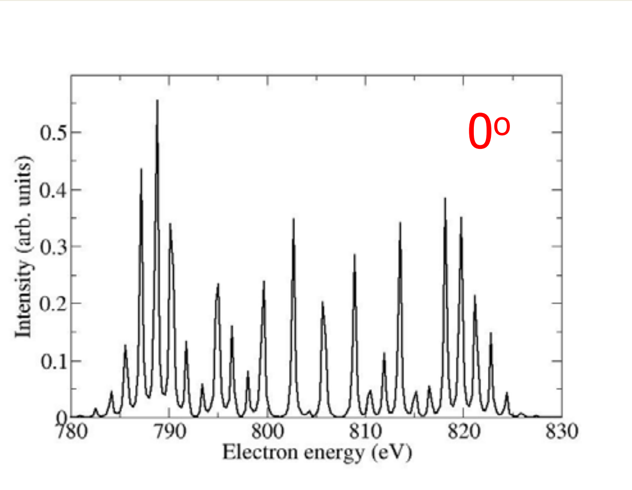


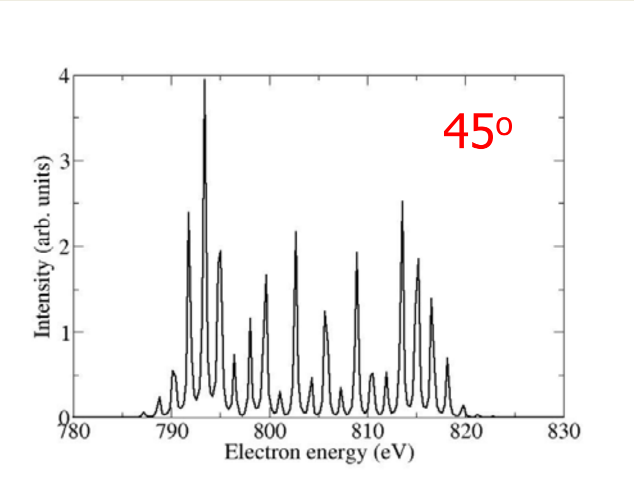
X-ray: τ_X = 1 fs

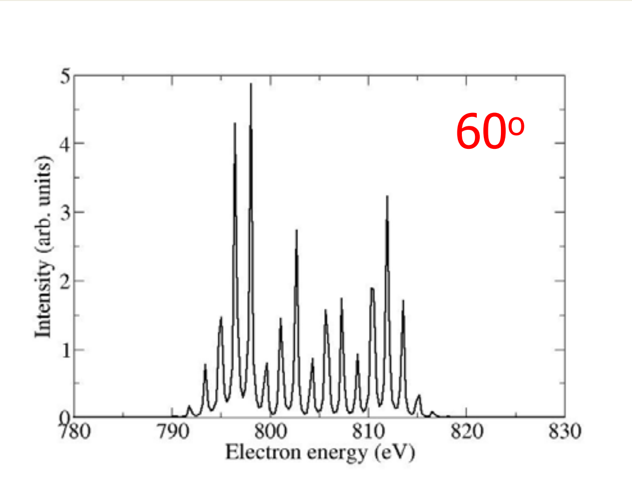
IR: τ_L = 20 fs

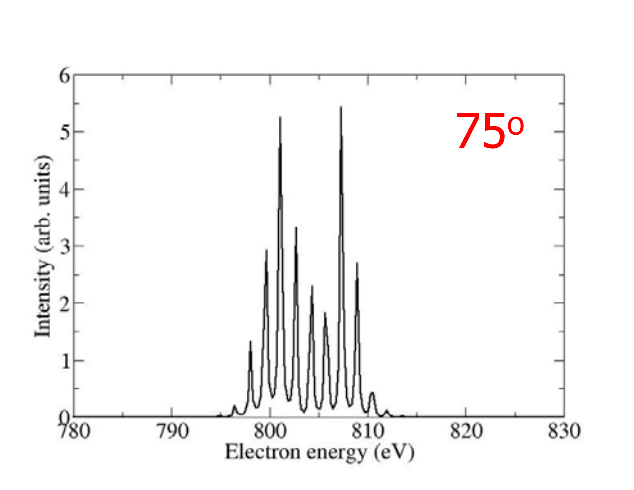


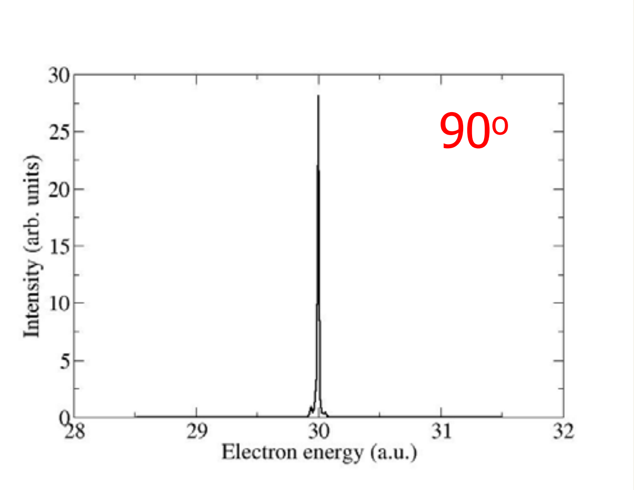
Sidebands at different emission angles



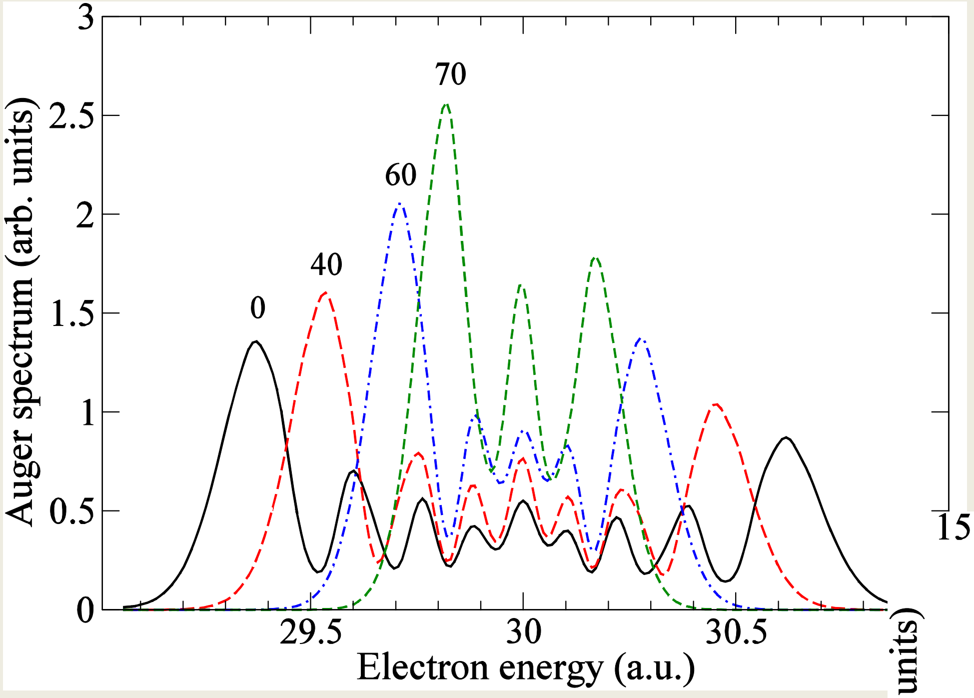




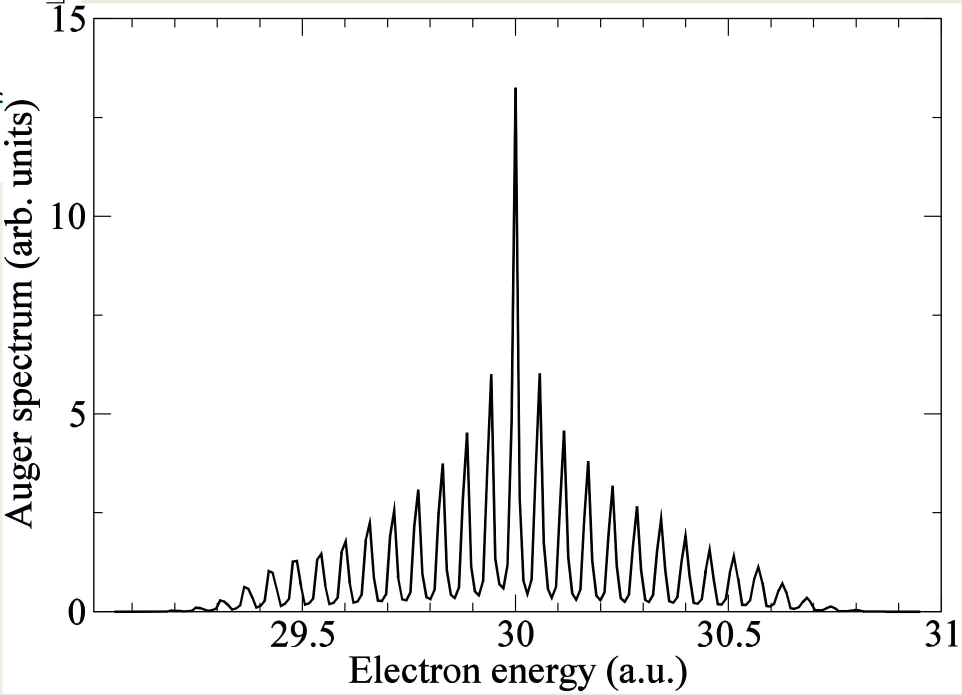




Angular dependence of the gross structure

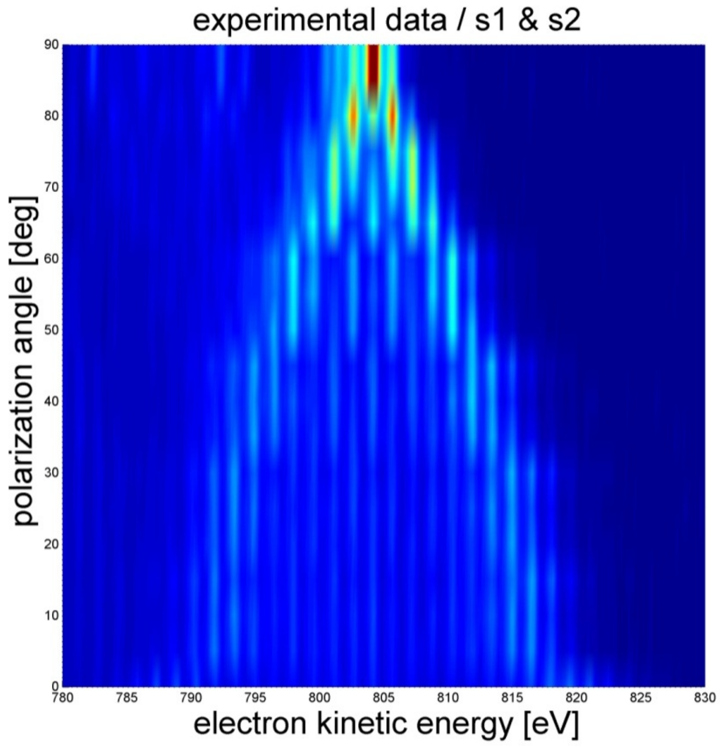


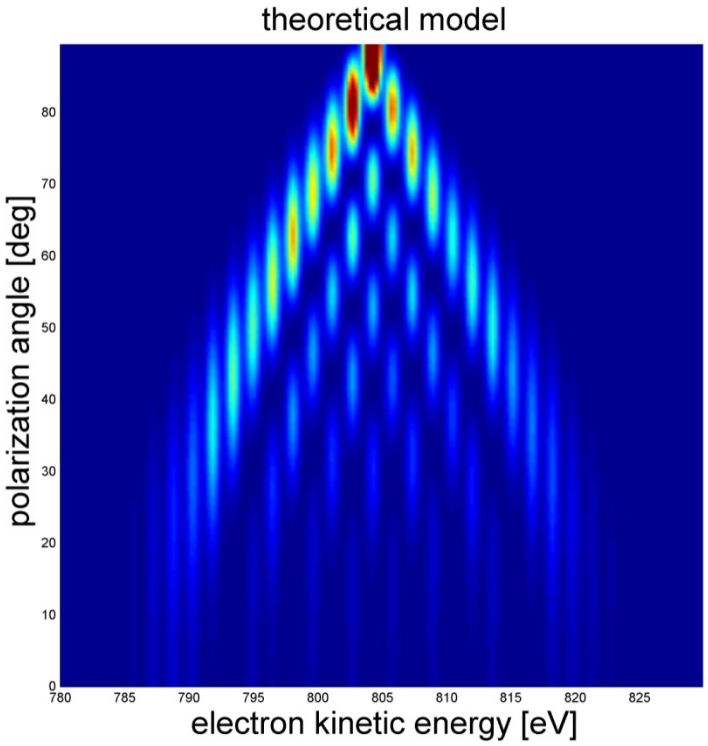
Angle-integrated spectrum



Recent experiment at LCLS

M. Meyer et al 2010 unpublished





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