Strong-field interactions in intense superposed extreme ultra-violet free-electron and infra-red laser fields

P. Radcliffe[1], W. B. Li[1], S. Düsterer[1], H. Redlin[1], J. Feldhaus[1], J. Dardis[2], P. Hayden[2], P. Hough[2], V. Richardson[2], J. T. Costello[2], M. Arbeiter[3], T. Fennel[3], D. Cubaynes[4], M. Meyer[4]

[1]*HASYLAB at DESY, Notkestr. 85, D-22607 Hamburg, Germany*
[2]*National Center for Plasma Science and Technology and School of Physical Sciences, Dublin City University, Dublin, Ireland*
[3]*Universität Rostock, Institut für Physik, Universitätsplatz 3, D-18051 Rostock, Germany*
[4]*LIXAM, UMR 8624, Université Paris Sud, Bâtiment 350, 91405 Orsay Cedex, France*

The development of high power, infra-red (IR) femtosecond lasers has uncovered a rich vein of non-perturbative phenomena in the bound-free and free-free transitions of atoms interacting with coherent light. It is at *strong-field* intensities at and above 10^{14}W/cm^2 that such behavior produces above threshold ionization (ATI), high-harmonic generation (HHG), and attosecond pulse generation [1, 2, 3]. The combination of extreme ultraviolet (XUV) and IR photons represents a particularly powerful method for the study of continuum transitions since the bound-free step can be made insensitive to atomic resonances by appropriate photon energy tuning or selection. We have studied the response of atomic neon exposed simultaneously to intense monochromatic XUV radiation from the free electron laser in Hamburg (FLASH) and a synchronized IR laser. Already at modest intensities the main photoelectron line is strikingly modulated by the IR dressing field, producing strong sideband features in the electron energy spectrum. As a precursor to more elaborate quantum mechanical calculations a classical model was considered, which reproduces the characteristics of the two-color signal at high intensities in a satisfactory manner.

The experiments were performed at beamline BL2 of FLASH, using a synchronized IR laser system

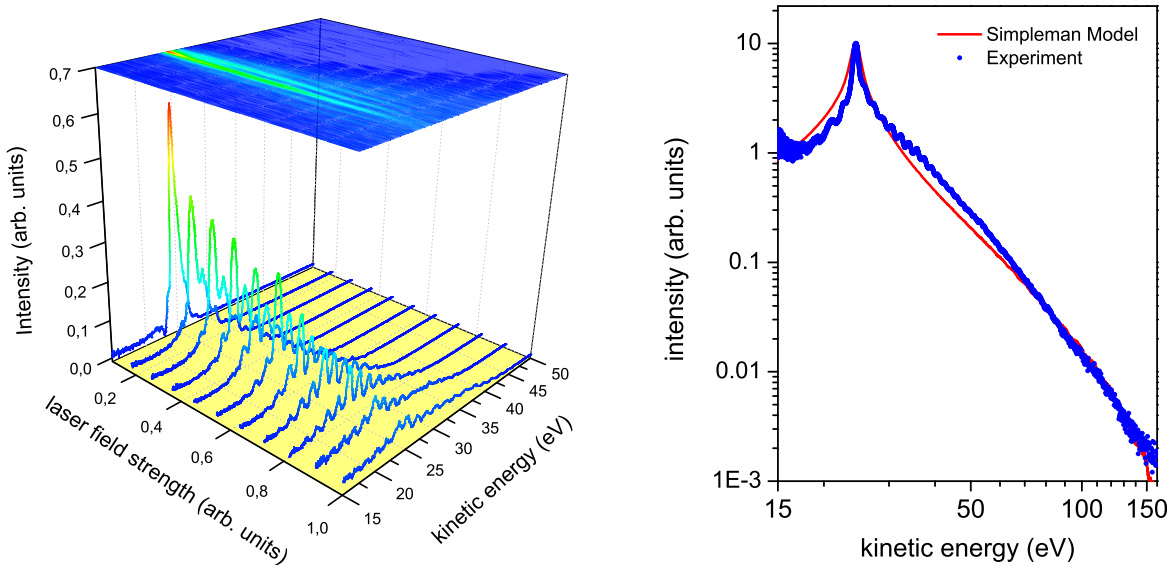

Figure 1: (left) Single-shot spectra of 2p photomemission in neon ($\hbar\omega_{XUV}$ = 46 eV) at the maximum temporal overlap. The spectra are arranged in terms of increasing laser electric field strength, up to a maximum $I_{IR} \sim 5\times10^{13}$ W/cm^2. (right, dots) Two-color electron spectrum at the increased IR field strength of 8×10^{14} W/cm^2, (line) corresponding results from a classical analysis of the kinetic energy spectra.

[4]. The lasers were introduced into the experimental chamber in a collinear geometry where they intersected an effusive gas jet. The resulting photoelectrons were detected with a magnetic bottle electron spectrometer (MBES), which allows single-shot acquisition. The FEL was operated in single-bunch mode at 5 Hz repetition rate and wavelength of 26.9 nm (46 eV) with a mean pulse energy of about 20 μJ. The IR laser system consisted of a low repetition rate (10 Hz), high power Ti:sapphire setup (800 nm, 120 fs, 2 mJ) producing a maximum peak intensity of 3×10^{15} W/cm^2 when focused. Both FEL and IR lasers have linear polarization parallel with the MBES axis.

In figure 1 (left) a series of single-shot electron energy spectra for Ne are shown. The spectra show one central line corresponding to the direct $2p \rightarrow \epsilon l$ photoline, accompanied by a nearly symmetric spread of high and low energy sidebands, which result from the stimulated absorption and emission of n laser photons [5]. The growth of the sidebands is matched by a corresponding decrease in the main photoline; i.e., the total electron yield remains constant, as the IR field does not contribute to the primary ionization process. By increasing the laser electric field strength the two-color energy spectrum extends to over 150 eV, see figure 1 (right). The high-intensity data can be interpreted in terms of a classical calculation, relying on the so-called Simpleman's model [6]. This model estimates the final kinetic energy U of an electron introduced into an IR field $E_{IR} = E_0(t)cos(\omega_{IR}t + \phi_0)$ with initial kinetic energy U_a = $\hbar\omega_{XUV}$ - IP_{Ne}. The photoelectrons will have final kinetic energies of

$$U = U_a - \sin(\phi_b)\cos(\theta_b)\sqrt{8U_aU_p} + 2U_p\sin^2(\phi_b) \quad (1)$$

where ϕ_b is the phase of the IR-field at the instant of ionization and θ_b is the angle between the light polarization and the initial velocity of the electron at birth. U_p is the instantaneous pondoromotive energy at the moment of birth t_b.

$$U_p = \frac{e^2E_0^2(t_b)}{4m_e\omega_{IR}^2} \quad (2)$$

In this simplified approach, atoms are ionized statistically by the XUV pulse and electrons are "born" into the IR field with an initial angular momentum distribution according to photoemission from the Ne 2p level at 46 eV photon energy (β_2 = 0.95) [7]. After the ionization process the ion potential is neglected and the photoelectron is propagated classically in the IR-field, i.e., the initial photoelectron momentum is shifted by the vector potential of the IR field at the time of birth. The final photoelectron spectrum is obtained from an ensemble average over a large number of statistically sampled trajectories, including focus averaging for equally sized XUV and IR beams and a timing jitter between the XUV- and IR-pulses [8]. In figure 1 the experimental photoelectron spectrum is compared to the result of the classical model. While the classical approach cannot explain discrete sidebands, the overall kinetic energy distribution of the spectrum is reasonably well described. This underlines that, on average, the action of the highly non-linear dressing field can be well described with the simplified classical picture.

References

[1] L. F. Di Mauro and P. Agostini, Adv. At. Mol. Opt. Phys. **35**, 79 (1995).
[2] P. Salières et al., Adv. At. Mol. Opt. Phys. **41**, 83 (1999).
[3] M. F. Kling and M. J.J. Vrakking, Annu. Rev. Phys. Chem. **59**, 463 (2008).
[4] P. Radcliffe et al., Nucl. Instrum. Meth. A **583**, 516 (2007).
[5] M. Meyer et al., Phys. Rev. Lett. **101**, 193002 (2008).
[6] J. M. Schins et al., Phys. Rev. Lett. **73**, 2180 (1994).
[7] "VUV and Soft X-Ray Photoionization", Eds. U. Becker and D. A. Shirley, Plenum Press: New York and London (1996).
[8] P. Radcliffe et al., Appl. Phys. Lett. **90**, 131108 (2007).