# Modification of high-order harmonic generation by an XUV field: retrieving the XUV-assisted photorecombination cross section

**T.S. Sarantseva[*,†1], M.V. Frolov[†,*], N.L. Manakov[†], N.V. Vvedenskii[*], and Anthony F. Starace[‡]**

[*] Institute of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod 603950, Russia
[†] Department of Physics, Voronezh State University, Voronezh 394018, Russia,
[‡] Department of Physics and Astronomy, The University of Nebraska, Lincoln NE 68588-0299, USA

**Synopsis** Analytic formulae for high-order harmonic generation (HHG) by atoms in an intense infrared laser field and a weak high-order (XUV) harmonic are derived. We show that the XUV field induces new channels for HHG, which involve absorption of the XUV photon at the ionization or recombination steps of HHG. The XUV-assisted recombination channel leads to a long second plateau in HHG spectrum, as reported in [1]. We show that the HHG yield in the second plateau region can be factorized in terms of an electron wave packet and the XUV-assisted photorecombination cross section, providing a further extension of HHG spectroscopy for retrieving cross sections of laser-assisted collision processes.

Over the past decade the high-order harmonic generation (HHG) process has became a useful tool for retrieving spectroscopic information about unperturbed atomic or molecular targets [2, 3]. The key concept of HHG spectroscopy lies in the factorization of the HHG yield in terms of an electron wave packet (EWP), $W(E)$, and a *field-free* photorecombination cross section, $\sigma(E)$, [4, 5]:

$$\mathscr{R}_{IR}(N) = W(E)\sigma(E), \quad E = N\omega - I_p, \qquad (1)$$

where $E$ is the returning electron energy, $N$ is the harmonic number, $\omega$ is the laser frequency and $I_p$ is the ionization potential of the target atom or molecule. The main advantage of this parametrization consists in the universality of the EWP describing the first two stages of HHG: the tunneling ionization and subsequent propagation of the liberated electron in the laser-dressed continuum along closed classical trajectories. The HHG amplitude can also be presented in terms of a laser factor, $w(E)$, and the field-free photorecombination amplitude, $a(E)$,

$$\mathscr{A}_{IR}(N) = w(E)a(E),$$

where $W(E) = p|w(E)|^2$, $p = \sqrt{2E}$.

Within the framework of the time-dependent effective range theory, we investigate here HHG in a two-color laser field, whose two components are linearly polarized in the same direction. The first component is an intense, infrared (IR) field and the second component is its weak high-energy (XUV) harmonic with frequency $\Omega$. Our analytical analysis shows that the $N$th harmonic amplitude has the form:

$$\mathscr{A}(N) = \mathscr{A}_{IR}(N) + \mathscr{A}_{XUV}(N),$$
$$\mathscr{A}_{XUV}(N) \approx w_\Omega(E)a(E) + w(E-\Omega)a_\Omega(E-\Omega),$$

where $a_\Omega$ is the single photon amplitude for *XUV-assisted* photorecombination.

The laser parameter $w_\Omega(E)$ describes the ionization of an electron by absorption of a single XUV photon and its propagation in the continuum along classical trajectories that differ from those for a single IR field. The maximum energy gain, $E_{\max}$, in this channel is smaller than for a single IR field and depends on the XUV photon energy.

The laser parameter $w(E-\Omega)$ coincides with the one for the IR laser field, but its argument is shifted by the XUV photon energy. In this channel the cutoff position is extended up to the energy $E_{\rm cut} \approx 3.17u_p + \Omega$, where $u_p$ is the ponderomotive energy in a single IR field. Thus only this term contributes to the HHG amplitude in the energy region between $3.17u_p$ and $3.17u_p + \Omega$. The HHG yield in this region has a factorized form similar to (1):

$$\mathscr{R}(N) = W(E-\Omega)\sigma_\Omega(E-\Omega), \qquad (2)$$

where $\sigma_\Omega$ is the *XUV-assisted* photorecombination cross section corresponding to absorption of the XUV photon. This factorization enables one to retrieve $\sigma_\Omega$ from the HHG spectrum. We also extend our analytic result to the case of real atoms by properly introducing Coulomb field effects.

## References

[1] A. Fleischer 2008 *Phys. Rev. A* **78** 053413

[2] H. J. Wörner *et al.* 2009 *Phys. Rev. Lett.* **102** 103901

[3] A. D. Shiner *et al.* 2011 *Nat. Phys.* **7** 464

[4] T. Morishita *et al.* 2008 *Phys. Rev. Lett.* **100** 013903

[5] M. V. Frolov *et al.* 2009 *Phys. Rev. Lett.* **102** 243901

[1] E-mail: sarantseva_ts@phys.vsu.ru