MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Novel light from high-order harmonic generation manipulated by XUV light

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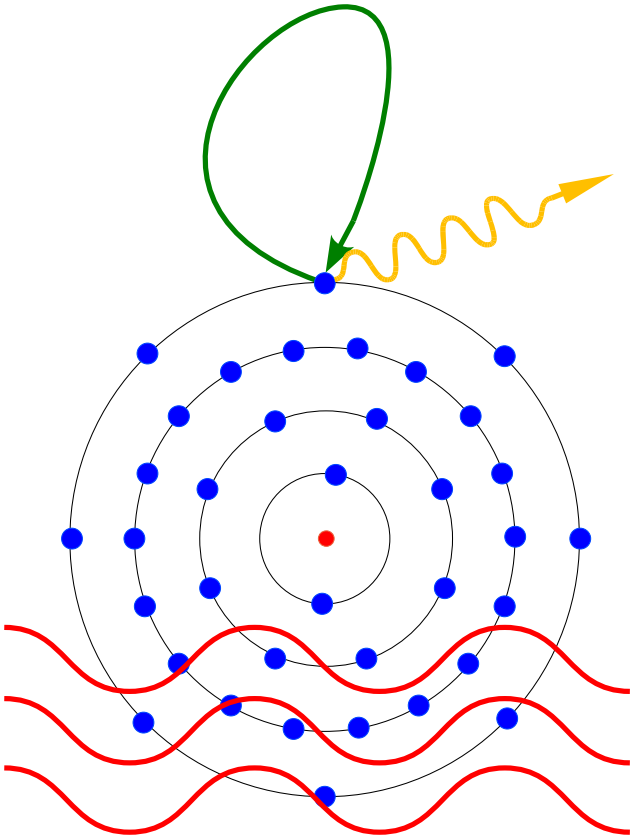
High harmonic generation (HHG)

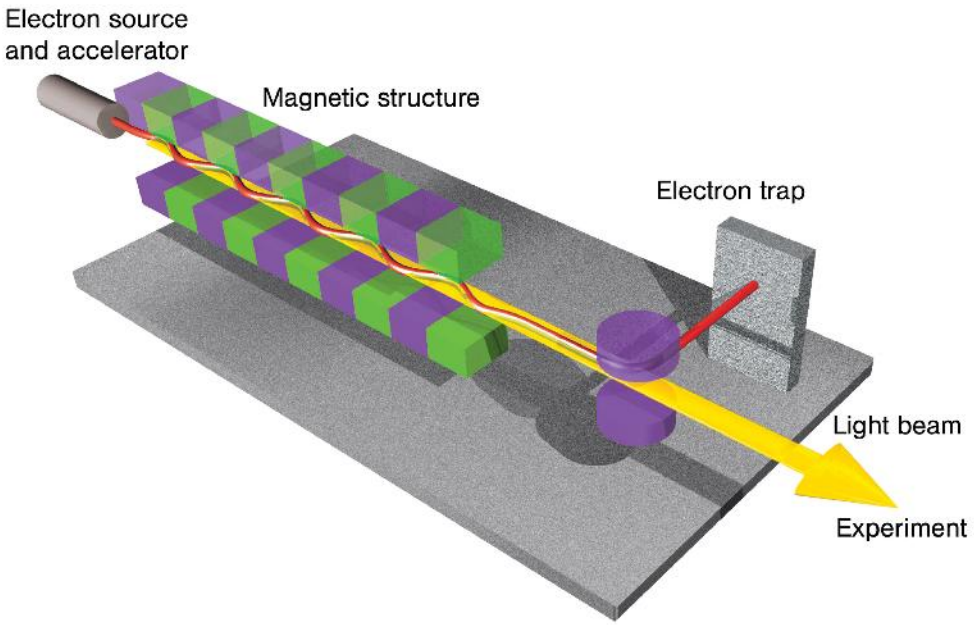
- High harmonic generation (HHG) by atoms in intense optical laser fields
- Theory mostly based on the **single-active electron** (SAE) approximation
- Restriction to HHG from **valence electrons**
- Two-electron scheme of a nonsequential double recombination
- HHG in the presence of XUV light with many-electron effects with a frequency-dependent polarization



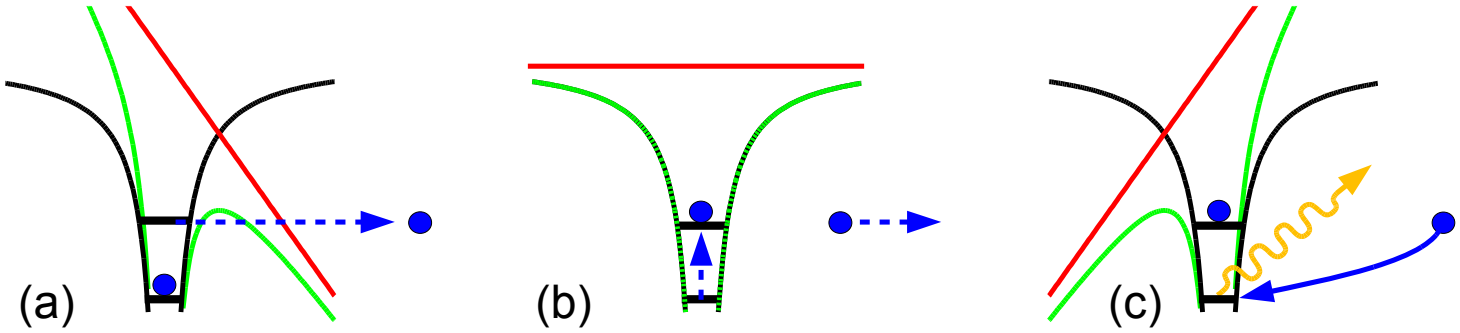
P. Kova, F. Wilken, D. Bauer, C. H. Keitel, Phys. Rev. Lett. 98, 043904 (2007)
A. Fleischer, Phys. Rev. A 78, 053413 (2008)

XUV/x-ray free electron lasers

- Free-electron laser in Hamburg (FLASH)
- Electrons emit x rays spontaneously
- Downstream: electrons interact with the radiation
- Self-amplified spontaneous emission (SASE)
- **Unprecedented XUV intensities**



HHG with XUV in terms of the three-step model



(a) the atomic valence is **tunnel ionized**

(b) free propagation in the electric field of the optical laser

(c) the electron **recombines** with the ion emitting HHG radiation

C. Buth, M. C. Kohler, J. Ullrich, C. H. Keitel, submitted, arXiv:1012.4930

Theory of resonant XUV excitation and HHG

- Two-electron basis states $|a\rangle\otimes|c\rangle, |\vec{k}\rangle\otimes|c\rangle, |\vec{k}\rangle\otimes|a\rangle$
- Hamiltonian $\hat{H}=\hat{H}_{\mathrm{A}}+\hat{H}_{\mathrm{L}}+\hat{H}_{\mathrm{X}}$
- Wavepacket

$$|\Psi,t\rangle=a(t)\,\mathrm{e}^{-\mathrm{i}\phi_1 t}|a\rangle\otimes|c\rangle+\int_{\vec{k}\in R^3}\left[b_a(\vec{k},t)\,\mathrm{e}^{-\mathrm{i}\phi_2 t}|\vec{k}\rangle\otimes|c\rangle+b_c(\vec{k},t)\,\mathrm{e}^{-\mathrm{i}\phi_3 t}|\vec{k}\rangle\otimes|a\rangle\right]\mathrm{d}^3k$$

- Equations of motion, Rabi matrix
- Dipole matrix element

$$\tilde{D}(\Omega)=-\mathrm{i}\sum_{\substack{i\in\{a,c\}\\ j\in\{+,-\}}}U_{ij}\,w_j\int_0^\infty\sqrt{\frac{(-2\pi\mathrm{i})^3}{\tau^3}}\,\mathrm{e}^{-\mathrm{i}F_{0,j}(\tau)}\sum_{N=-\infty}^{\infty}\mathrm{i}^N J_N\left(\frac{U_{\mathrm{P}}}{\omega_{\mathrm{L}}}C(\tau)\right)\mathrm{e}^{-\mathrm{i}N\omega_{\mathrm{L}}\tau}$$
$$\times\sum_{M=-\infty}^{\infty}\check{b}_{M-N,i}(\tau)\,h_{M,0,i}(\Omega,\tau)\,\mathrm{d}\tau$$

- Harmonic photon number spectrum (HPNS) along x axis

$$\frac{\mathrm{d}^2P(\Omega)}{\mathrm{d}\Omega\,\mathrm{d}\Omega_{\mathrm{S}}}=4\pi\,\Omega\,\rho(\Omega)|\tilde{D}(\Omega)|^2$$

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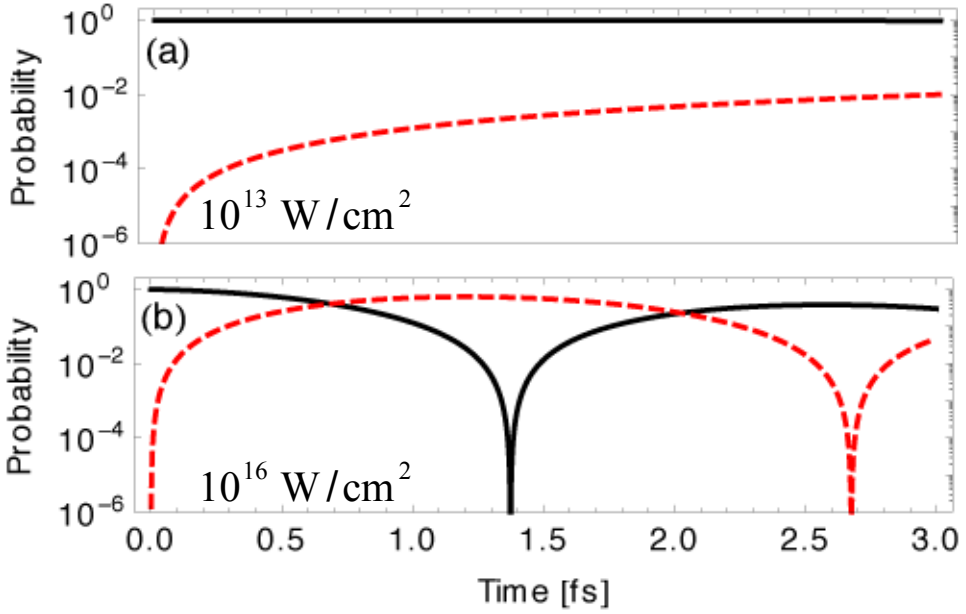
Rabi flopping in a two-level system

- Two-level system in **cation** $|\vec{k}\rangle \otimes |c\rangle$ and $|\vec{k}\rangle \otimes |a\rangle$
- Probabilities to find the electron in the valence or the core state
- Excursion time of electron for an 800 nm laser ≈ 1 fs
- **Rabi oscillations** on the time scale of HHG



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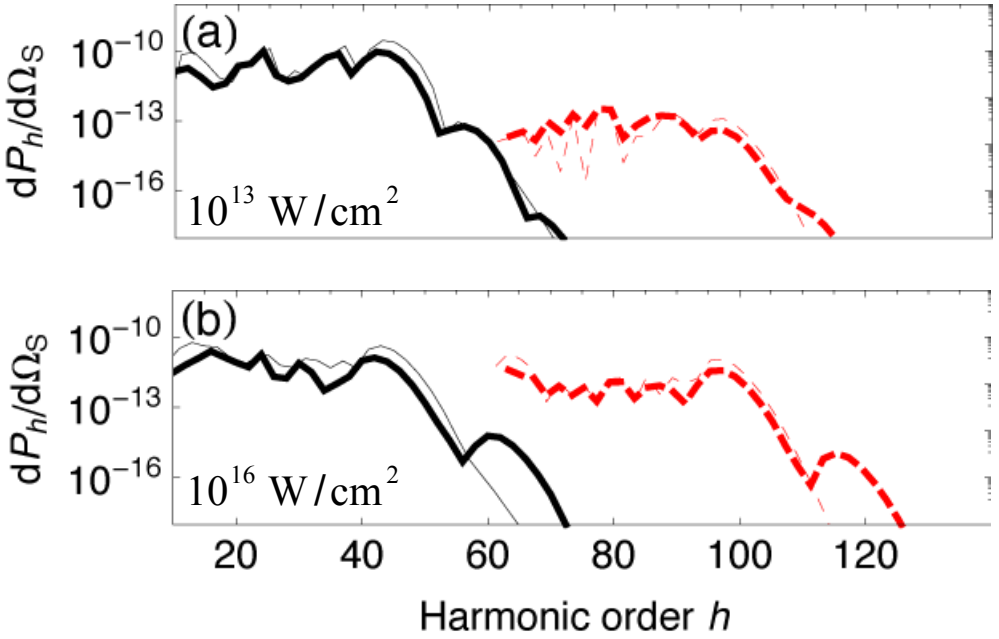
HHG spectra for semi-CW laser and XUV light

- HHG spectra of **krypton**
- 800 nm laser and XUV light with **constant amplitude** starting at t = 0 s
- Valence 4p, core 3d
- Transition $|c\rangle \rightarrow |a\rangle$ by XUV
- Core recombination is determined by probability to find electron in the valence hole



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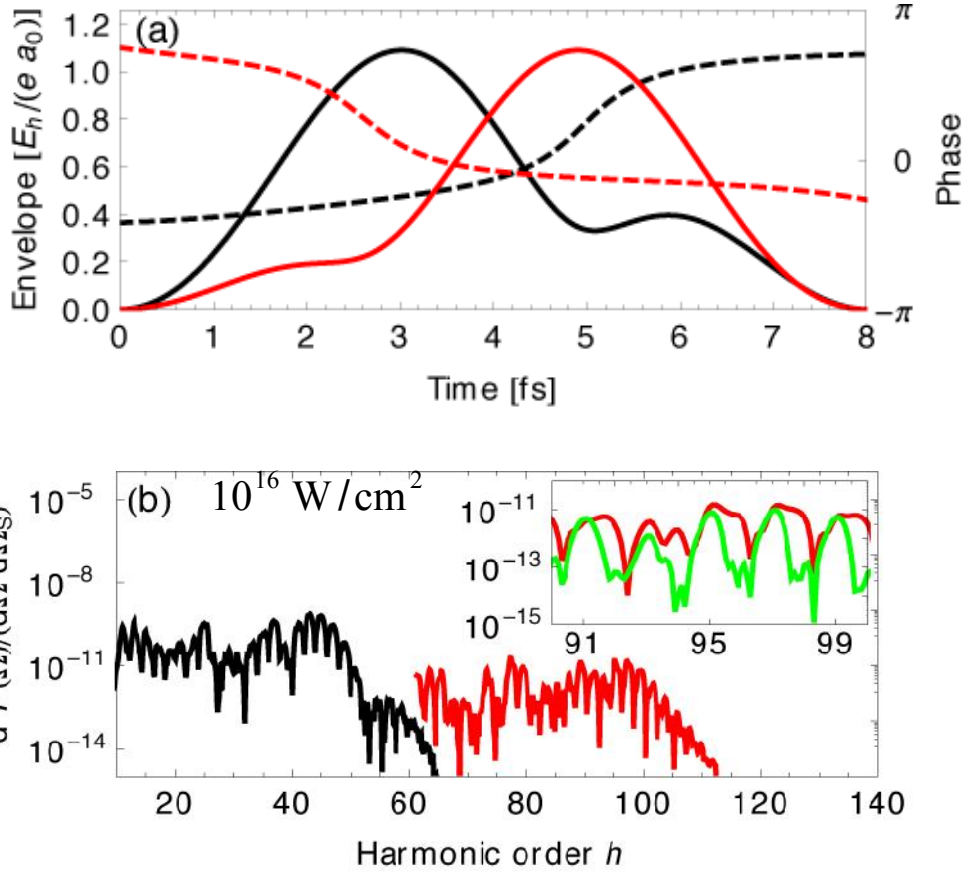
HHG with a SASE FEL pulse

- SASE pulse of FELs is only **partially coherent**
- Sensitive dependence of HHG on XUV pulse shape
- Upconversion of HHG by XUV excitation leads to **novel light**



C. Buth, M. C. Kohler, J. Ullrich, C. H. Keitel, submitted, arXiv:1012.4930

T. Pfeifer, Y. Jiang, S. Düsterer, R. Moshammer, J. Ullrich, Opt. Lett. 35, 3441 (2010)

Applications of the novel light

- Generate isolated **attosecond x-ray pulses**

  E. Goulielmakis *et al.*, Science 320, 1614 (2008)

- Reconstruction of SASE FEL pulses with **frequency resolved optical gating** (FROG)

  R. Trebino, *Frequency-resolved optical gating: the measurement of ultrashort laser pulses* (Kluwer Academic Publishers, Boston, Dordrecht, London, 2000)

- Ultrafast time-dependent **chemical imaging** of core holes

  T. Morishita *et al.*, Phys. Rev. Lett. 100, 013903 (2008)

C. Buth, M. C. Kohler, J. Ullrich, C. H. Keitel, submitted, arXiv:1012.4930

Conclusion

- **Two-color physics**: XUV free electron lasers and optical lasers
- Valence HHG induced by optical laser
- XUV light leads to **resonant excitation** of intermediate ion
- Recombination of continuum electron with core hole
- **Nonlinear upconversion** of HHG light
- Potential for exciting applications

Acknowledgment

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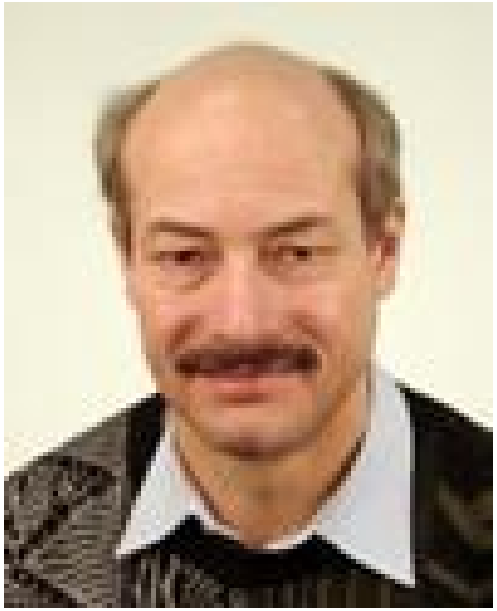

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