Plenary Talk PV V Wed 9:00 PV-Rooms

Science at the Timescale of the Electron: The Quantum Nonlinear Optics of High Harmonic Generation — •Margaret M. Murnane — JILA, University of Colorado, Boulder, CO 80309-0440, USA

The same revolution that visible lasers underwent in the 1960s is now happening for tabletop coherent X-ray sources. In nonlinear optics, the high electric fields that are present in a focused laser beam can drive electrons in a highly irregular (anharmonic) motion, re-radiating harmonics of the driving laser light at much shorter wavelengths. Although its physical manifestation is very different, high harmonic generation (HHG) can be thought of as a coherent laser-driven version of the Rontgen X-ray tube. In HHG, the laser field intensity is sufficient to ionize the atom. For the few-femtosecond time interval during which this is happening, the laser-driven quantum wavefunction of the electron can radiate coherent high harmonic X-ray beams, which have spectacular temporal and spatial coherence. This is because of the ultra-precise timing relationship between the laser and X-ray fields, and the acceleration of the electron quantum wavefuction, that are all synchronized to less than an attosecond (or $<10^{-18}$ seconds).

Very recently, the full power of extreme nonlinear optics for manipulating the quantum wavefunction of a radiation electron has been realized. Simply by changing the color and polarization of the driving laser, the HHG spectrum, pulse duration and polarization can be exquisitely controlled.[1-4] One recent surprising finding is that *longer* wavelength mid-infrared lasers can generate *shorter* wavelength bright X-ray beams. Using 4μm driving lasers for example, HHG emerges as a broad coherent supercontinuum, spanning the entire electromagnetic spectrum from the ultraviolet (UV) to the soft X-ray keV region of the spectrum, to wavelengths < 8 Å. Moreover, these X-rays emerge as isolated attosecond bursts, that are predicted to scale to the sub-attosecond (i.e. zeptosecond) regime using longer wavelength lasers. In contrast, using intense UV driving lasers, HHG emerges as a series of bright narrow-band peaks, with ≈ 10 fs pulse duration. Finally, by manipulating the electron wavefuction using bi-chromatic (two-color) circularly polarized counter-rotating laser beams, it is now possible to produce bright circularly polarized harmonics (ideal for studying chiral media), to complement the bright linearly polarized HHG beams available for 20 years. The powerful quantum coherence of HHG make it ideal for imaging the fastest dynamics relevant to function in atoms, molecules, nanosystems and materials, at multiple atomic sites simultaneously. [5-10]

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[2] Chen et al., PNAS, vol. **111**, pp. E2361-E2367 (2014)
[3] Kfir et al., Published online, Nature Photonics, *DOI: 10.1038/NPHOTON.2014.293* (2014)
[4] Hernandez-Garcia et al., Physical Review Letters **111**, 033002 (2013)
[5] Mathias et al., PNAS **109**, 4792 (2012)
[6] Rudolf et al., Nat. Comm. **3**, 1037 (2012)
[7] Turgut et al., Physical Review Letters **110**, 197201 (2013)
[8] Seaberg et al, Optica **1**, 39 (2014)
[9] Siemens et al., Nature Materials **9**, 26 (2010)
[10] Nardi et al., Postdeadline presentation, Conf. on Ultrafast Phenomena, Japan (2014)