High-Harmonic and Attosecond-Pulse Generation, Measurement and Application

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Synopsis Attosecond technology represents three advances in one. Each implies applications: (1) We introduce a new form of nonlinear optics; (2) We synthesize the world's shortest pulses; (3) We control XUV radiation with long wavelength beams, allowing the XUV beam, for example, to focus even without X-ray optics.

In conventional nonlinear optics, bound states describe an electron moving within a quantum system resulting in harmonic generation, but the system always returns to the initial state when it emits coherent photons. If it were not so, phase-matched radiation would not be possible. With attosecond pulses, continuum states play the role of bound states. Thus, in extreme nonlinear optics (1) we free an electron, (2) the electron moves in the continuum under the influence of the strong laser field and (3) it recombines joining the population already present in the original state [1]. Phase matching is still essential. We can never side-step returning to the initial state of the system.

Without perturbation theory as a guiding approximation to high intensity interactions, for extreme nonlinear optics we use classical physics, or the strong field approximation (a semi-classical generalization) for intuitive insight. This is valid because classical physics well describes the motion of electrons in the continuum. Controlling the continuum electron is critical for generating, measuring or applying attosecond pulses.

There are two similar approaches to measuring attosecond pulses – both rely on manipulating the ionized electron.

1. Often called streaking or RABBIT [2], one uses an attosecond pulse (or train of pulses) that has already been produced to irradiate a well understood quantum system, creating photoelectrons that are born into a time-dependent infrared field. The electron's energy (or even phase) serves as an indelible label relating the photoelectron properties with the electron's spectral phase. For a well understood quantum system, we can determine the range of IR-fields in which the electron is generated – the attosecond pulse duration. Delaying the IR pulse relative to the attosecond pulse provides two-dimensional data for a FROG-like algorithm. Alternatively, we can measure the dynamics of a quantum system of interest with a well understood attosecond pulse.
2. Often called perturbative measurement or *in situ* measurement, one uses an intense infrared pulse that will ionize an electron and ultimately creates an attosecond pulse that we will observe. A perturbing pulse can modify the recollision electron's trajectory between birth and recombination. This changes the XUV spectrum encoding the times of birth and recollision including any phase of the transition moments from the initial (bound) state to the final (bound) state [3]. Delaying the perturbing pulse relative to the strong driving pulse provides two-dimensional data for a FROG-like algorithm.

As with all of ultrafast optics, there are many approaches to measurement. One approach is streaking – we time resolve electrons emitted by an attosecond pulse from different levels (or bands) in atoms (or solids) with an infrared field that labels the spectral phase of any electron ionized by the attosecond pulse.

Transient absorption spectroscopy is extensively applied in conventional ultrafast optics. It can be generalized to attosecond phenomena by using an intense beam as a pump to initiate attosecond dynamics. Changes in the absorption spectrum reveal ultrafast dynamics of the system under investigation stimulated by the pump.

References

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[2] Paul, P.M. et al. 2001 *Science* **292**, 1689
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