Stopping time for atoms and electrons

To fully understand how physical processes work, we have to be able to watch them evolve over time. We do this by taking pictures at regular intervals while the phenomenon of interest is occurring; a well-known tool for almost all scientists. If you want to be able to study the motions of electrons in atoms, however, you are presented with a problem; the entire trajectory or process that you want to record is likely to happen in less than $1x10^{-15}$s (1 femtosecond).

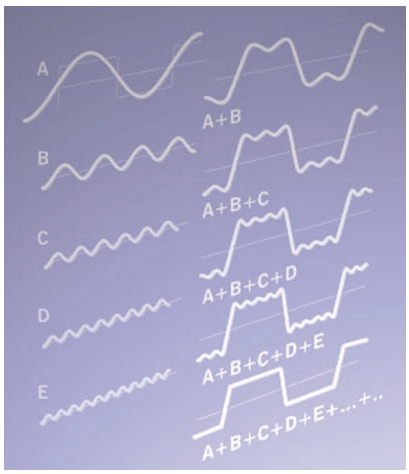
Since femtosecond pulses are currently the shortest available to provide a stroboscopic or "stop-action" light source, this means that we can only observe time averages of phenomena at this temporal scale. However, a collaboration lead by researchers at Imperial College London are hoping to push the state of the art by an order of magnitude, producing a controllable stream of 200-attosecond ($1x10^{-18}$s—as) pulses with a repetition-rate of 1kHz.

The challenges to be overcome to produce these pulses—and then make use of them—are formidable. Perhaps the most difficult is generating the light. Light pulses, though they seem to be a single color, are actually made up of many different frequencies. From Fourier theory (see figure), different component waves are necessary to shape the beam temporally. To produce this kind of pulse therefore necessitates forcing lots of electronic transitions (releasing photons of different wavelengths), all of which must be triggered at the same time (so that the emissions are in phase).

This is particularly difficult, but possible. One way of doing it, for instance, is known as high-order harmonic generation (HHG). When a femtosecond pulse of laser light is pumped into the material, it causes what can be thought of as an electronic recollision effect: All of the electrons are driven away and then pulled back to their parent nuclei by the oscillating electric field. As they come back they release photons, all at the same time, and in the right combination to produce a pulse of the order of 200as long. This technique has only recently become available; the laser intensity required to trigger this extreme reaction is more than $100TWcm^{-2}$. However, it has the advantage that, since one laser pulse triggers one HHG pulse, controlling the output is relatively straightforward.

As an alternative that promises more pulse energy, they have another mechanism to exploit: Raman scattering. This is the emission of light due to changes in the vibrational or rotational energy levels of a molecule. Careful stimulation of the molecules with nanosecond laser pulses can produce pulses of less than a femtosecond, of the order of 500as. Though this isn't as short enough for true attosecond metrology, it should assist in the development of some of the auxilliary technology required.

Having this extra source may prove crucial, because the developing attosecond imaging tools will require much more than just attosecond sources. Once produced, the pulses must be optically manipulated. Again, the multitude of frequencies is a problem here. For each one, the optical elements the pulse must propagate through will have a different refractive index, which means that the shape of the pulse will change as some of the light is slowed down relative to the other frequencies, and some is speeded-up. This problem is made worse by the fact that the light is centred on a frequency in the extreme ultraviolet: a band for which the quality of optical materials is poor.



Square-wave pulses are made up of a combination of constituent sine waves of different frequencies

And of course, once the light has been used to probe the species under investigation, it must be detected. The team have a plan to use a low-resolution camera technique initially, but hope, eventually, to be able to record the full picture.

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