

Physicists routinely exploit femtosecond light pulses to track the movement of atoms in molecules, and are now developing sources that emit even shorter bursts of X-rays to study and control the motion of electrons inside atoms

From femtochemistry to attophysics

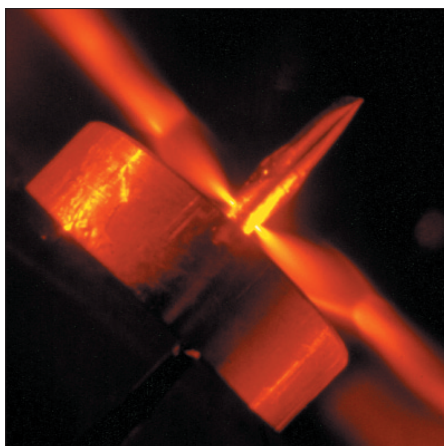
Ferenc Krausz

MANY amateur photographers are disappointed when they discover that their shots of fast-moving objects are blurred beyond recognition. The most likely reason for this is that the exposure time was not short enough to freeze the motion. In contrast, modern ultrahigh-speed cameras can take up to a million images every second and can capture motion that is normally imperceptible to the human eye. By projecting the photographs on a screen in sequence, the action can be replayed in slow motion. While these techniques are ideal for studying macroscopic objects, how can we possibly follow the motion of atoms and electrons?

The impetus to be able to track the movement of atoms and electrons comes from many areas of science and technology. The ability to look at chemical or biochemical processes is a prerequisite for steering reactions, while insights into the dynamics of electrons and holes in semiconductor structures are crucial for speeding up electronic devices. At a more fundamental level, following the motion of electrons in atoms is essential if we want to understand what happens inside excited atoms and exploit these processes in applications such as X-ray lasers.

So how short does the exposure have to be in order to capture the dynamics of atoms and electrons? Surprisingly, the answer is rooted in classical physics and is determined by the mass of the atom and the Coulomb force exerted on it by its neighbours. The movement of nuclei in a molecular or crystal-lattice structure, for example, can be traced with a probe lasting 10–100 femtoseconds ($1 \text{ fs} = 10^{-15} \text{ s}$). Meanwhile, the smaller mass of electrons makes them rather snappy movers. Indeed, the motion of bound electrons in excited atoms and molecules evolves on timescales of 10–1000 attoseconds ($1 \text{ as} = 10^{-18} \text{ s}$) and so requires attosecond probes.

Taking freeze-frame shots of atoms calls for exposures more than a million times shorter than those offered by the fastest high-speed cameras. This enormous gap has been



Ultrafast X-ray pulses are generated when neon atoms contained in this metal tube are irradiated with a femtosecond laser

bridged in the last decade thanks to the invention of lasers that produce flashes of light lasting just a few femtoseconds.

Atoms in slow motion

Physicists can now take snapshots of evolving atomic systems with pinpoint accuracy using ultrashort flashes of light to *both* trigger the dynamics *and* illuminate the system. This can be done by splitting each laser pulse with a partially transmitting mirror and delaying the less energetic “probe” pulse with respect to the stronger excitation or “pump” pulse (figure 1). In this way a powerful femtosecond laser pulse can initiate the same microscopic process in millions of molecules or sites in a crystal lattice. A weaker

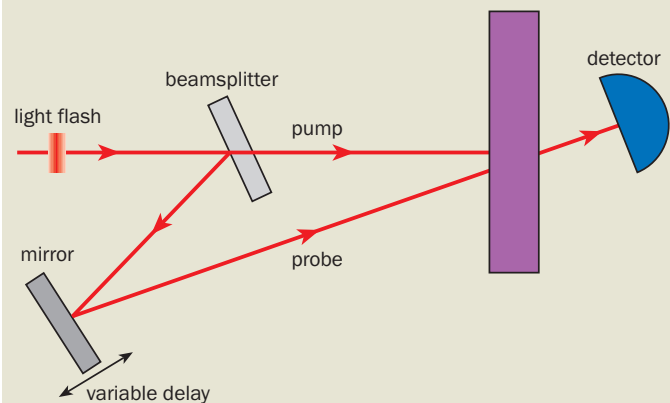
portion of the pulse (or a frequency-shifted replica) can then probe the dynamics by measuring changes in the optical properties of the system (e.g. the absorption) at a later instant.

We can replay the atomic or molecular dynamics in slow motion by using a series of femtosecond pulses and increasing the delay between successive pump and probe pulses. This approach is known as time-resolved or pump–probe spectroscopy and is currently the only way to study microscopic dynamics. The time resolution is only limited by the duration of the pump and probe pulses.

Physicists can now routinely generate pulses shorter than 10 fs using self-mode-locking lasers, which were invented in 1990 by Wilson Sibbett of St Andrews University in Scotland. In a mode-locked laser, the electric fields associated with all the different frequencies or modes that can exist inside the laser cavity add constructively at one point and destructively elsewhere to create a high-intensity spike.

The early mode-locked lasers developed in the 1970s were difficult to construct and operate. In contrast, self-mode locking happens naturally in carefully designed laser cavities that incorporate a solid-state amplifier such as titanium-doped sapphire – a laser medium developed in the 1980s by Peter Moulton at the Massachusetts Institute of Technology. Meanwhile

1 High-speed photography at the microscale



To extend high-speed photography to microscopic processes, an ultrashort laser pulse is split in two at a beamsplitter. The excitation or pump pulse initiates the dynamics, e.g. the breaking of a chemical bond, while the probe pulse captures any change in the optical properties at a later time. A sequence of measurements can be made by varying the delay between the pump and probe pulses using a movable mirror. From the change of the optical properties (e.g. absorption) versus delay, the dynamics (e.g. atomic motion) can be reconstructed. The duration of the light flashes determines the resolution of this “time microscope”.

specialized “chirped” mirrors, devised in 1993 by Robert Szipöcs of the Research Institute for Solid State Physics and Optics in Budapest and the current author, can further compress the pulses (see Szipöcs *et al.* in further reading).

Using these techniques, Ursula Keller at the ETH in Zurich and, independently, Franz Kärtner and colleagues at MIT, have developed oscillators that produce pulses that last just 5 fs and have a wavelength of 800 nm. In other words, these pulses contain only two cycles of the laser field. Since light is an electromagnetic wave, the laser pulses cannot be shorter than the “carrier wavelength”, λ , which therefore limits the duration of the pulse to λ/c , where c is the speed of light.

This means that the wavelength of light limits the resolution with which atoms can be observed in time, as well as limiting the spatial resolution (see the article by Vahid Sandoghdar on page 29). Interestingly, physicists can resolve atoms more readily when they are moving than when they are fixed. While it is impossible to view stationary atoms with visible light due to the diffraction limit, femtosecond pulses are capable of tracking moving atoms that are displaced by as little as 0.01 nm in real time due to the fact that the atoms move slowly compared with the speed of light.

Femtosecond chemistry and semiconductor dynamics

The formation and breaking of chemical bonds between atoms in molecules is one of the most important microscopic processes that affect our lives. Ultrafast laser pulses allow physicists and chemists to follow these femtosecond processes by tracing the displacements of the atoms, as demonstrated for the first time in the late 1980s by Ahmed Zewail at the California Institute of Technology. These displacements induce changes in the optical properties of the weakly bound valence electrons that can be revealed instantly by a visible-light probe. In complex systems, however, the atomic motion can be more accurately determined by studying core electrons close to the atomic nucleus, but this requires X-ray wavelengths.

Ultrafast laser pulses also allow us to measure the frequencies with which the chemical bonds stretch and contract.

However, molecular vibrations can be measured more easily in the frequency domain using existing techniques, for example by measuring the absorption of infrared radiation as a function of frequency. So what are the advantages of ultrafast lasers?

Unlike frequency-domain techniques, ultrafast lasers provide access to the relative phase of the vibrational modes, which is crucial for reconstructing the dynamical changes in the structure of the molecule. These time-domain measurements can identify which chemical bond broke first, for instance, and the course of the chemical reaction. Moreover, femtosecond pulses can even control chemical reactions, as demonstrated recently by Gustav Gerber and Thomas Baumert at the University of Würzburg in Germany.

Ever since they became widely available, picosecond and femtosecond lasers have been used to investigate the dynamics of charge carriers in semiconductors. New insights into the basic phenomena that limit the speed of integrated circuits allow physicists to extend the limits of high-speed electronics. Ultrashort pulses of light can be used to explore the frontiers of electronics because they are far faster than the fastest electronic devices available.

Moreover, the terahertz electric fields that are produced by ultrashort optical pulses can induce and control currents in integrated circuits on timescales that are inaccessible to electronic instruments. This capability will help to speed up computers by a factor of thousand compared with the current state of the art. And even when terahertz electronics becomes a reality, femtosecond laser pulses will still be fast enough to keep pushing the frontiers of semiconductor technology.

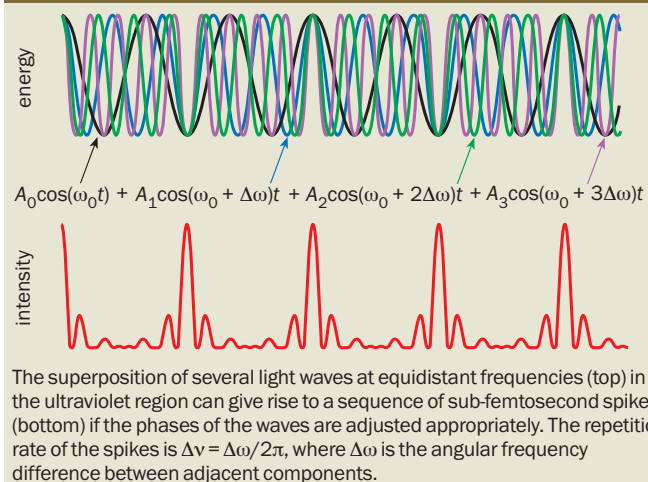
Beyond the femtosecond barrier

So can we gain anything more by improving the resolution of pump-probe spectroscopy beyond 1 fs? The answer is clearly yes – sub-femtosecond laser pulses will enable us to track processes *inside* atoms for the first time. The first step in this direction is to generate and measure sub-femtosecond or attosecond light pulses. These pulses will have to be substantially shorter than the wave cycle of visible light, which lasts about 2 fs in the case of red light. As a result, shorter wavelengths or higher “carrier frequencies” are needed to generate sub-femtosecond light pulses.

In principle, a sequence of light pulses that are shorter than λ/c can be produced simply by adding together waves that oscillate with an angular frequency of $\omega_0 + N\Delta\omega$, where $\Delta\omega$ is a fixed shift with respect to the fundamental laser wave, $\omega_0 = 2\pi c/\lambda$, and N is an integer (figure 2). The result is a series of intense spikes separated in time by $1/\Delta\nu = 2\pi/\Delta\omega$.

The duration of these spikes is inversely proportional to both the frequency shift, $\Delta\nu$, and the number of waves that add together. This means that in order to produce the sub-femtosecond pulses using a limited number of waves, $\Delta\nu$ must be similar to the frequency of visible light. Conceptually, this technique is closely related to the mode-locking method that is generally used to generate femtosecond pulses in laser resonators (see Kapteyn and Murnane in further reading). The significant difference, however, is that $\Delta\nu$ for sub-femtosecond pulse generation must be several orders of magnitude greater than the frequency spacing between the adjacent modes of a laser resonator. Indeed, $\Delta\nu$ must be so large that no laser can amplify all these frequency-shifted waves. The only way that these waves can be produced is using nonlinear

2 How to generate sub-femtosecond pulses



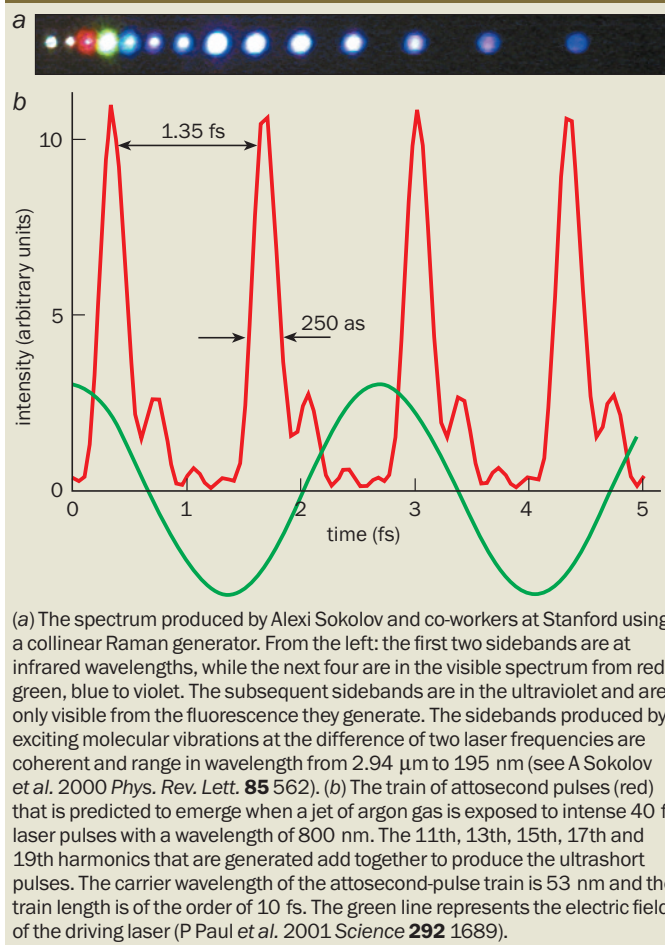
optical techniques that are not part of the femtosecond laser oscillator itself.

In general, two nonlinear optical phenomena can be exploited to produce waves that are phase-coherent with the incident laser beam but have much higher frequencies – stimulated Raman scattering and high-order harmonic generation. In order to keep the dispersion of ultraviolet light and the absorption of shorter wavelengths as low as possible, both processes are carried out in a gas.

Raman scattering occurs when light passes through a gas of molecules. The light can excite vibrational or rotational energy levels in the molecules, which subsequently modulate the laser radiation. The potential of stimulated Raman scattering for generating trains of sub-femtosecond pulses has been demonstrated by several groups, including Alexi Sokolov and Stephen Harris at Stanford University in the US. They excited vibrational oscillations in deuterium molecules using two narrow-band lasers, which were chosen so that the difference in frequency between the two beams matched the oscillation frequency of the molecules. The periodic movement of the deuterium nuclei affects the extent to which the electrons are displaced by the laser. This periodic nuclear motion leads to phase-coherent sidebands that are frequency shifted with respect to the incident laser waves by the vibrational frequency ($\Delta\nu \approx 90$ THz). The spectrum of these coherent collinear Raman modes extends from the infrared to the ultraviolet (figure 3a). Only a fraction of this spectrum – comprising the blue, violet and ultraviolet lines – is needed to generate a train of sub-femtosecond pulses separated by $1/\Delta\nu \approx 11$ fs, provided the relative phase of the Raman modes is properly adjusted.

Even shorter pulses can be produced by shifting the laser frequency into the extreme ultraviolet using high-order harmonic generation. This phenomenon occurs when a high-power beam of linearly polarized femtosecond laser pulses is passed through an atomic gas. The intense electric field of the light pulse can rip an electron away from an atom and then accelerate it. When the light field reverses in the next half-cycle, the electron can slam back into the ion and give up its energy in the form of an X-ray photon. This process is repeated every half cycle of the laser field, resulting in the emergence of discrete lines in the extreme ultraviolet and X-ray spectrum. These “high-order harmonics” are separated in

3 Raman sidebands and high harmonics



(a) The spectrum produced by Alexi Sokolov and co-workers at Stanford using a collinear Raman generator. From the left: the first two sidebands are at infrared wavelengths, while the next four are in the visible spectrum from red, green, blue to violet. The subsequent sidebands are in the ultraviolet and are only visible from the fluorescence they generate. The sidebands produced by exciting molecular vibrations at the difference of two laser frequencies are coherent and range in wavelength from 2.94 μm to 195 nm (see A Sokolov *et al.* 2000 *Phys. Rev. Lett.* **85** 562). (b) The train of attosecond pulses (red) that is predicted to emerge when a jet of argon gas is exposed to intense 40 fs laser pulses with a wavelength of 800 nm. The 11th, 13th, 15th, 17th and 19th harmonics that are generated add together to produce the ultrashort pulses. The carrier wavelength of the attosecond-pulse train is 53 nm and the train length is of the order of 10 fs. The green line represents the electric field of the driving laser (P Paul *et al.* 2001 *Science* **292** 1689).

frequency by twice the frequency of the driving laser field and combine with each other to produce a train of attosecond pulses (figure 3b).

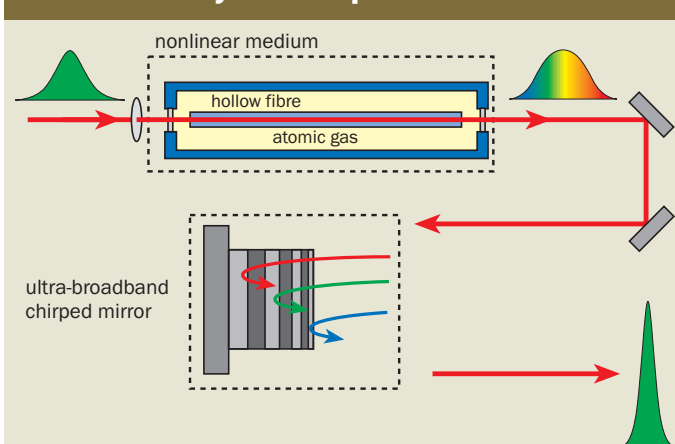
Conclusive experimental evidence for the existence of such a pulse train was obtained only recently by a collaboration between French and Dutch physicists, led by Harm Geert Muller at the FOM Institute for Atomic and Molecular Physics in Amsterdam and Pierre Agostini at the Centre d'Etudes de Saclay near Paris. The experiment indicated the generation of a train of 250 as pulses using 40 fs pump pulses from a Ti:sapphire laser.

Sub-femtosecond spectroscopy

Stimulated Raman scattering and high-harmonic generation unfortunately have their drawbacks for pump-probe spectroscopy. The time interval between the pulses – 11 fs in the Stanford experiment and 1.3 fs in the Amsterdam-Paris work – is so short that the physical, chemical or biological processes under study do not have time to completely decay and return to their initial state before the next pulse arrives. The high repetition rate of the pulses therefore imposes an unacceptably severe restriction on the processes that can be studied.

Clearly pump-probe spectroscopy can only benefit from these ultrafast sources if a single pulse can be selected from the train, as Paul Corkum of the Steacie Institute of Molecular Sciences in Ottawa, Canada, pointed out in his pioneering proposal for attosecond optics. The most promising way of isolating such a pulse is to drive the molecules that produce the

4 Intense few-cycle laser pulses



To produce high-energy light pulses comprising less than three wave cycles, 20 fs pulses from a Ti:sapphire laser are first propagated through a hollow-core waveguide filled with neon. The intensity-dependent refractive index of the gas modulates the pulse, resulting in the emergence of new frequency components. The leading edge of the pulse is “red-shifted” to lower frequencies while the trailing edge is “blue-shifted” to higher frequencies. When these pulses impinge on a specially designed “chirped” multilayer mirror, the red-shifted components at the front edge penetrate deeper before being reflected than the blue-shifted components at the trailing edge. This mirror compresses the frequency-broadened pulse in time. The system is capable of delivering 5 fs pulses with a peak power of 0.1 terawatt (S Sartania *et al.* 1997 *Opt. Lett.* **22** 1526–1528).

Raman lines – or the atoms that emit the high harmonics – for such a short time that a single pulse naturally arises from the generation process. This avoids the formidable task of having to select individual pulses from a multi-terahertz train.

This approach requires that pulses from a Ti:sapphire laser must last no longer than 5–10 fs and must have about a millijoule of energy to produce a single sub-femtosecond burst of ultraviolet or X-ray radiation. But the 5–10 fs pulses that emerge directly from a Ti:sapphire laser oscillator have nanjoules of energy, rather than millijoules. Amplifying this energy by a factor of a million comes at the cost of stretching the pulses in time to about 20 fs.

One way around this problem is to take the intense 20 fs pulses and pass them through a hollow waveguide filled with a gas, a device that was invented in 1995 by Orazio Svelto and Sandro De Silvestri of Politecnico di Milano in Italy. Since the refractive index of the gas varies with intensity, the pulse broadens in frequency – the leading edge of the pulse is shifted to a lower frequency while the trailing edge is shifted to a higher frequency. These frequency-broadened pulses are next compressed in time using ultra-broadband “chirped multilayer mirrors” that were developed by my group in Vienna and researchers at Budapest (figure 4). These mirrors are specially designed so that the red-shifted light at the leading edge of the pulse penetrates further before being reflected than the blue-shifted light at the trailing edge. The emerging pulse is less than 10 fs in duration and has a peak intensity in excess of 100 gigawatts. Pulses with these characteristics are opening the way to the generation of single sub-femtosecond pulses.

The first successful steps in this direction were taken recently by exploiting both Raman scattering and high-harmonic generation. Georg Korn and co-workers at the Max Born Institute in Berlin passed 15 fs pulses of violet light through pre-excited sulphur-fluoride molecules with a vibrational frequency of 23 THz. Continuous sidebands were

generated, which resulted in the emergence of single pulses that had a wavelength of 400 nm and that last just 4 fs.

In another recent experiment, my group – in collaboration with researchers at the University of Bielefeld in Germany and the National Research Council of Canada in Ottawa – generated single soft X-ray pulses with a wavelength of 14 nm. These isolated X-ray bursts emerged as a collimated laser-like beam from high-harmonic generation in a gas of neon atoms exposed to intense pulses containing a few cycles of the laser field. We measured an upper limit of some 2 fs on the pulse duration by using the X-ray burst as a “pump” pulse to photo-ionize a gas of krypton atoms, and a second time-delayed laser as a “probe” (see Drescher *et al.* in further reading).

The techniques we developed offer the potential for generating and measuring single attosecond X-ray pulses. Theoretical calculations predict that the X-ray pulses emerging from our experiment lasted 600 as, but to verify this value experimentally requires either higher-energy X-ray pulses or more efficient measurement apparatus (figure 5a).

X-rays are not dispersed as widely in materials as ultraviolet pulses, which means that X-ray pulses lasting 100 as are quite robust. However, their production efficiency is far inferior to that of ultraviolet pulses. Now that there are suitable techniques for generating and measuring single X-ray pulses lasting 100–200 as, research must focus on enhancing the X-ray yield from high-harmonic generation for reliable attosecond pump-probe spectroscopy.

As a first application, we used a series of our 1.8 fs pulses to capture snapshots of the 7 fs laser that was used to generate the X-rays (figure 5b). This allowed us to resolve the intensity profile (i.e. the shape) of a light pulse lasting several femtoseconds for the first time.

Towards attophysics

Physicists are now close to controlling the motion of electrons on a timescale that is substantially shorter than the oscillation period of visible light. Indeed, in our experiment the electric dipoles of the neon atoms may have been set oscillating at the highest frequencies for just a few hundred attoseconds by an intense ultrashort laser. We can also use pulses containing a few cycles of the light field to rip an electron wavepacket from the core of an atom and set it free with similar temporal precision.

The specific time structure of both these processes depends on the evolution of the laser field within the optical cycle. This evolution is, in turn, affected by the relative phase of the carrier wave with respect to the amplitude envelope, the so-called carrier-envelope phase. For example, if the carrier-envelope phase of the laser pulse in figure 5a is shifted by $\pi/2$, then the electric field would reach a maximum at the centre of the pulse, rather than zero. In a pulse containing less than three oscillations, this phase shift can significantly modify the evolution of the electric and magnetic fields, and thereby affect the electron trajectories.

The first experimental indications of this phase dependence were observed recently by Gerhard Paulus and Herbert Walther at the Max Planck Institute of Quantum Optics near Munich and collaborators from the Politecnico di Milano. Meanwhile, Stephen Cundiff and co-workers at the JILA laboratory in Boulder, Colorado, and, independently, a collaboration between researchers at Vienna and Munich, have drawn on an ingenious idea of Theodor Hänsch at

MPI Munich to stabilize the carrier-envelope phase of ultrashort low-energy pulses.

Once amplified high-intensity pulses with a stabilized phase become available, strong-field processes – such as optical-field ionization or high-order harmonic generation – will allow us to measure the carrier-envelope phase directly. Access to this parameter – together with a measurement of the variation in amplitude and the frequency of the laser field using standard techniques – will allow us to determine and control the evolution of the electromagnetic field in a light wave, and even to synthesize arbitrary waveforms of light containing a few cycles.

Such waveforms might allow us to control the motion of an electron after it has been detached from an atom or a molecule. Direct consequences include the reliable generation and control of attosecond pulses at extreme ultraviolet and soft X-ray wavelengths via high-order harmonic generation. And at much higher intensities it may be possible to accelerate attosecond electron pulses up to several mega-electron-volts in energy.

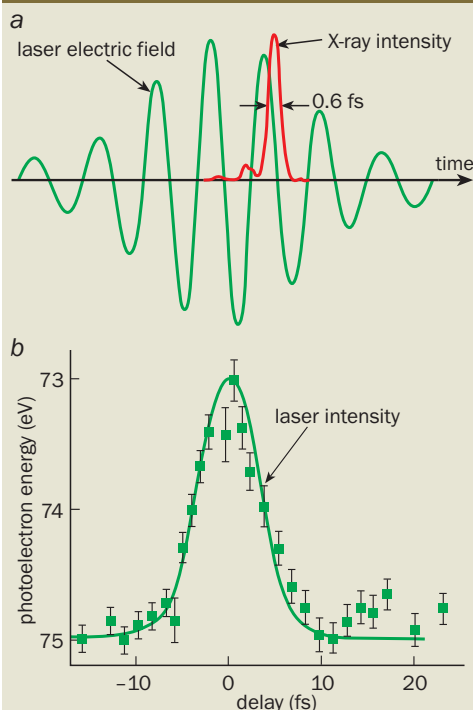
Since these X-ray and electron pulses are synchronized to the laser field with attosecond precision, we will be able to take snapshots of different stages of atomic, molecular and plasma dynamics. These processes will be triggered and steered by the intense field-controlled waveforms of light and probed by X-ray pulses, enabling us to both control and reconstruct the motion of electrons at atomic length scales and with attosecond resolution. In this way, for example, the trajectory of an electron wavepacket might be measured from the instant it is ejected from the atom and could be tailored for different applications. These applications might include the development of more efficient and shorter-wavelength X-ray lasers, or sources of ultrafast, monoenergetic relativistic electron pulses for the next-generation of particle accelerators.

Looking into atoms

Attosecond X-ray pulses will also pave the way towards watching the motion of electrons *inside* atoms. For example, we expect to be able to track the motion of an electron within a femtosecond of it being set free from a bound state by an intense laser field. We could also follow the relaxation of the remaining bound electrons to their new equilibrium states with attosecond resolution.

Once we can generate attosecond pulses with much higher energies, we will be able to use them as both pumps and probes in pump–probe spectroscopy. We could then selectively remove electrons from the inner shells with a strong

5 Attosecond pulses in action



(a) The predicted intensity envelope of the X-ray pulse (red) generated in a high-order-harmonic experiment with neon gas and near-infrared laser pulses lasting 7 fs (green). The isolated X-ray pulse is calculated to last 600 as and have a wavelength of 14 nm. Measuring the duration of such short pulses is challenging. The first measurement reported by a collaboration of Austrian, German and Canadian physicists set an upper limit of approximately 2 fs (see Drescher *et al.* in further reading). It should be possible to further improve the measurements. (b) The intensity versus time profile of a 7 fs laser pulse was recorded using 1.8 fs X-ray pulses to knock an electron out of an atom. The energy shift of the electron is proportional to the intensity of the longer laser pulse at the instant of X-ray absorption. By measuring this energy shift as a function of delay between the laser and X-ray pulse (points), the intensity (line) was reconstructed with a resolution dictated by the X-ray pulse duration. This is the first “time-microscope” measurement with a resolution approaching 1 fs.

attosecond X-ray pulse and probe the filling of the inner-shell vacancy to an accuracy better than 1 fs using a weaker time-delayed replica of the same pulse. Is there any need for this? Why not simply depend on the relaxation times derived from linewidth measurements? The simple answer is that the influence of an ultrashort intense field on the bound-electron dynamics – important for applications such as X-ray lasers – cannot be studied in the frequency domain.

Finally, back to basics. Bohr’s simple model of the hydrogen atom predicts that the electron takes about 150 as to orbit around the proton. According to the laws of quantum mechanics, no observable dynamics takes place as long as the electron resides in its ground state ($1s$). However, this situation changes if a fraction of the electron wavefunction is excited into the first excited state ($2s$). The time-dependent Schrödinger equation predicts that the two components ($|1s\rangle$ and $|2s\rangle$) of the new composite wavefunction will beat at a frequency equal to the transition frequency between the $1s$ and $2s$ energy levels (figure 6).

This beating gives rise to a cyclic change in the radial probability distribution of the electron with a period of about 400 as. This “breathing” of the hydrogen atom may be regarded as one of the most fundamental quantum dynamic phenomena in nature. But can it be observed? According to Armin Scrinzi and Thomas Brabec from the Vienna University of Technology, it might be detectable by exploiting the fact that the electron can be detached more easily when it is

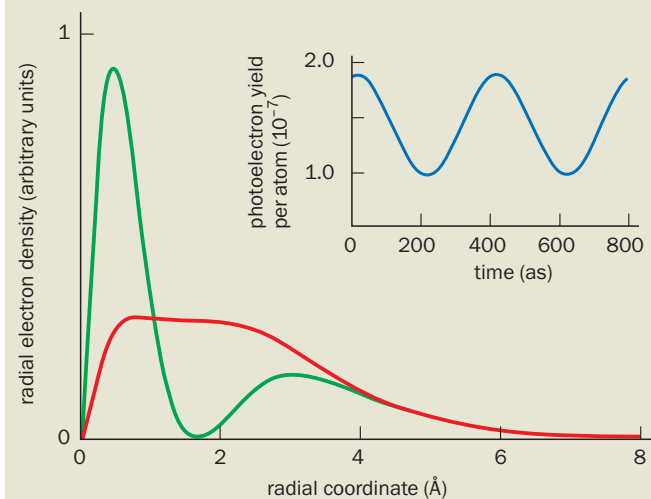
closer to the atomic core. They predict that measuring the photoionization yield with X-ray pulses shorter than 200 as in a pump–probe experiment might provide direct insight into this quantum dynamics. Although it is only of academic interest at the moment, inner-shell quantum beats may eventually be exploited, for example as clocks for future ultrahigh-speed molecular electronics operating beyond 1 THz.

Outlook

Ultrashort flashes of light allow us to take snapshots of microscopic particles and let us reconstruct their motion. State-of-the-art femtosecond lasers emit pulses that are short enough to resolve the motion of atoms in molecules and solids, as well as charge-carrier dynamics in semiconductors. Meanwhile, specially tailored femtosecond pulses also allow these processes to be controlled and will lead to numerous applications in chemistry, biochemistry and electronics.

The frontiers of both time-resolved spectroscopy and the control of microscopic dynamics are about to be radically

6 Attosecond breathing of the hydrogen atom



The radial electron density of a 1s–2s superposition state of hydrogen. The time-dependent Schrödinger equation predicts that the wavefunction oscillates between states of maximal (green) and minimal (red) electron density with a period of about 400 as near the nucleus. According to theoretical calculations, this fundamental quantum phenomenon may be observable using attosecond X-ray pulses that ionize the hydrogen atom. Theory predicts that the ionization yield will be modulated at the “breathing” period as a function of the time delay between the attosecond X-ray pulse and the excitation pulse (see insert).

extended due to the emerging technical capability that will allow us to synthesize intense pulses containing a few cycles of the laser field that evolve in a precisely determined way. With this technique we will soon be able to control the motion of electron wavepackets on attosecond timescales, just as we can currently control the motion of nuclear wavepackets within a few femtoseconds. The single attosecond X-ray pulses and attosecond electron bunches that will arise from our ability to control electron wavepackets will enable us to probe and steer electron motion with unprecedented precision.

The availability of these tools will herald a new age of experimental physics that will be so radical and so widespread that it will demand a new name. Get ready to welcome the era of attophysics.

Further reading

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www.femtolasers.com

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