crowave frequency is above a multiple of the cyclotron frequency. (In 2DES, if the transverse Hall conductivity dominates the DC response, the longitudinal resistance is actually proportional to the longitudinal conductance.) A similar effect has been observed in a different system: James Allen (University of California, Santa Barbara) and colleagues found zero and negative conductance when driving periodic semiconductor superlattices with intense terahertz radiation.[9]

The Yale group's calculations using a simplified model for the impurity potential reproduce not only the period of the observed resistance oscillation, but also the phase found by Mani and company. An explicit connection between the calculations and the observed zero resistance was put forward by Anton Andreev (University of Colorado) and colleagues at Columbia University,[10] who noted that a negative conductivity makes the 2DES unstable (a point also made by Anderson and Brinkman[7] and by Anatoly Volkov of the University of Bochum, Germany[11]). Andreev and coworkers showed that this instability causes the system to develop a domain structure with an inhomogeneous current pattern, for which the measured resistance would be zero. Andreev notes that the resistance oscillations indeed look like they could have swung negative but have instead been truncated at 0. Willett's observation of negative voltages may lend support to the idea of inhomogeneous current flow.

Other explanations have also been proposed. James Phillips (Rutgers University) has associated the vanishing resistance with sliding charge-density waves and open orbits.[12] Alexei Koulakov and Mikhail Raikh (Utah) have suggested that the behavior is due to a nonquadratic dependence of the electron energy on the momentum.[13] And Sergey Mikhailov (Stuttgart) attributes the behavior to microwave excitations of electron states around the edge of the 2DES.[14] He suggests that a combination of bulk and edge responses could account for the different phases observed for the resistance oscillations and for the temperature dependence. It could also reconcile the new experimental results with earlier experiments on less clean samples that, instead of oscillations, showed peaks in the resistance corresponding to the excitation of plasma waves in the sample.

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Ultrashort Laser Pulses Beget Even Shorter Bursts in the Extreme Ultraviolet

The attophysics frontier is about to expand, thanks to the newly won ability to control the phase of amplified laser pulses.

To fill a vacancy in a lower-lying atomic shell, an orbiting electron has to shed energy. If it follows the Auger process, the shell-hopping electron transfers its excess energy to a neighboring electron in the same shell. Left behind with too much energy, the neighbor quits the atom. The eviction takes a few tens to a few thousands of attoseconds (10^{-18} s)—at least that's what the energy spectrum of the ejected electrons implies. To track this and other excitation processes, one needs an attosecond probe.

Optical lasers capable of emitting pulses that last a few femtoseconds (10^{-15} s) already exist. At the 750-nm central wavelength of the popular Ti:sapphire laser, a single cycle of the electric and magnetic fields lasts 2.5 fs. Although it's possible in principle to make optical pulses shorter than a single cycle, that feat is beyond current materials and methods.

But, as Paul Corkum of Canada's National Research Council proposed 10 years ago, there is a way to use optical laser pulses to generate bursts that breach the femtosecond barrier.[1] The key lies in exploiting the effect of the laser's electric field on atoms. If the laser beam is powerful enough, its electric field effectively lowers the atom's Coulomb barrier to the point that valence electrons can escape through tunneling. The electrons' taste of freedom is brief, however. Half a cycle later, the field reverses and yanks the electrons back to their atoms. Figure 1a illustrates the process.

Some of the recaptured electrons reoccupy their original orbitals, but to do so they must dump the energy they gained from the field. The energy ends up in a burst of extreme ultraviolet (EUV) or soft x-ray photons. Thanks to the driving laser pulse, the emission is coherent. Each burst lasts a few hundred attoseconds.

But getting a burst every half-cycle isn't especially useful. In pump–probe experiments, for example, a pump pulse provokes an excitation whose relaxation is measured by a subsequent probe pulse. By gradually varying the delay between the pump and probe pulses, one samples the lifetime of the process under study. A string of bursts of fixed and narrow separation lacks the flexibility for such an approach. Single, controllable bursts are better.

Two collaborating teams have just filled that need.[2] Ferenc Krausz of the Vienna University of Technology, Austria, and Theodor Hänsch of the Max Planck Institute for Quantum Optics in Garching, just north of Munich, Germany, can now make isolated bursts of precisely controlled and reproducible shape that last a few hundred attoseconds. Of course, a few hundred attoseconds isn't the same as a few attoseconds. Even so, this most

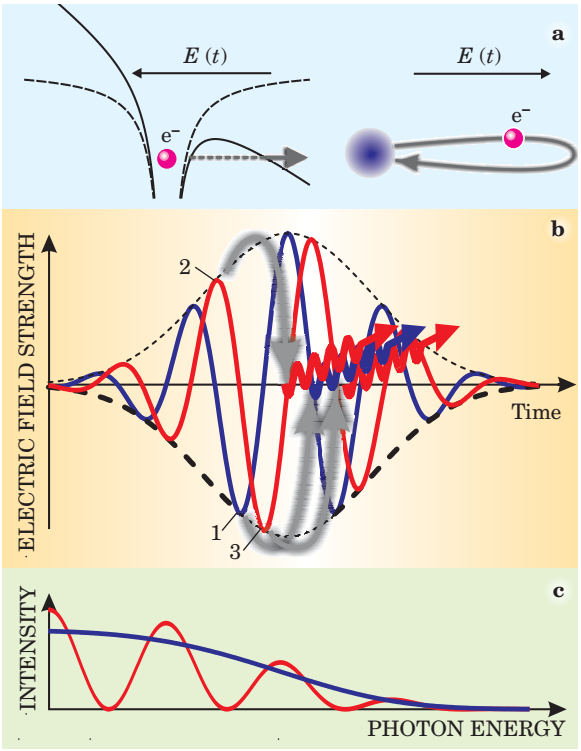

Figure 1. Electrons slam back into their parent atoms, as shown in **(a)**, after a strong electric field lowers their confining potential. **(b)** For a given pulse intensity, peak-energy bursts are emitted when the return half-cycle of the field is strongest. In the case of the blue "cosine" oscillation, electrons (whose motions are indicated with gray arrows) begin to tunnel free at time 1. Half a cycle later, at the highest peak of the oscillation, the electrons start rushing back to their parent atoms. The process ends with the emission of a single peak-energy burst (wavy blue arrow). In the case of the red "sine" pulse, the electrons that start tunneling at times 2 and 3 experience the same restoring force. **(c)** As a result, the oscillation produces two peak-energy bursts (wavy red arrows).

recent order-of-magnitude reduction in pulse duration augurs new opportunities in ultrafast atomic physics.

From femto to atto

Inevitably, the two or so cycles that occupy the envelope of a few-fs laser pulse vary significantly in amplitude and, therefore, in the energy they can bestow on valence electrons. Could an energy filter be used to let through only one highest-energy burst per pulse? As figure 1b shows, the answer is no. Two differently phased oscillations can fit within the envelope; both can engender bursts that can surmount an energy threshold.

What Krausz calls the cosine pulse (the blue curve in figure 1b) begets one peak burst, whereas the sine pulse (the red curve) begets two. To select the more desirable cosine pulse, the Munich–Vienna team looked for a property of the burst emission that varies with the phasing of the oscillations with respect to the peak of the envelope—that is, with respect to what's called the carrier-envelope phase.

The discriminator turned out to be spectral. In general, the energy spectrum of a burst includes harmonics from the interaction between the electrons and the electric field. That's true whatever the carrier-envelope phase, but at the highest energies, the spectra from the cosine and sine oscillations differ. As figure 1c indicates, the sine oscillation's two bursts interact with each other to produce further harmonics, but in the cosine phase, the spectrum is featureless.

By measuring the x-ray spectrum, the Munich–Vienna team could identify the carrier-envelope phase. But that's not much use if the phase jitters and drifts after each measurement. To control the phase, one must first stabilize it. For that task, the team adapted the frequency comb technique that Hänsch and his coworkers pioneered four years ago (see PHYSICS TODAY, June 2000, page 19).

A frequency comb consists of a precisely and evenly separated series of harmonics that extends from the near infrared through the visible spectrum. In developing the frequency comb, Hänsch aimed to measure frequencies for establishing time standards and for doing atomic spectroscopy. For those applications, the laser doesn't have to be powerful. But to reach the millijoules needed to rip electrons from atoms, the laser light must be amplified by a factor of more than a million. Krausz and Hänsch worried that amplification would destroy the phase control, but Krausz's carefully engineered amplifier, part of which appears in figure 2, turned out to contribute no more than 0.016π of phase jitter.

Phase drift was another problem. As the pulses bounce back and forth in the amplifier, they acquire additional and variable phase. To keep

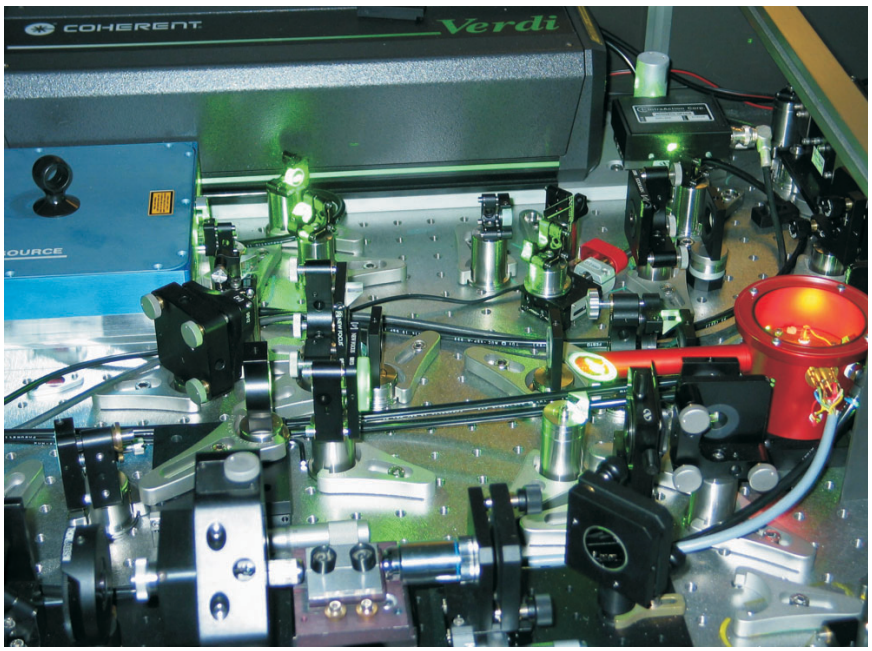

Figure 2. Some components of the attosecond setup can be seen in this photo. The long box at the top of the picture contains the pump laser, which seeds the Ti:sapphire oscillator (the blue box on the left). The oscillator generates the frequency comb. Amplification takes place in the red cylindrical device on the right. (Courtesy of Matthias Uiberacker, Vienna University of Technology.)

track of the drift, Krausz and Hänsch used what they call an *f*-to-2*f* interferometer. Conceived in Hänsch's group three years ago, the *f*-to-2*f* interferometer looks at the interference between the blue end of the spectrum and the red end of the second harmonic. When the carrier-envelope phase is stable, the spectrum of the combined signal shows a pattern of fringes that yields the phase.

Using the interferometer, Krausz and Hänsch found that the carrier-envelope phase wanders back and forth by about $\pi/4$ on a timescale of a few seconds. The relative slowness of the drift makes it straightforward to control the carrier-envelope phase. A computer-controlled feedback loop monitors the output of the *f*-to-2*f* interferometer: If the carrier-envelope phase wanders off, the feedback mechanism pulls it back by introducing a correction before the pulses are amplified. In this way, Krausz and Hänsch can lock the carrier-envelope phase with a precision of $\pi/10$ for as long as they run the laser.

To prove that they could indeed control the carrier-envelope phase and produce attosecond bursts, Krausz and Hänsch aimed the stabilized, amplified pulses at a few cubic millimeters of neon gas. As they expected, the spectrum from phase-stabilized bursts was harmonic. But only when the carrier-envelope phase was zero—that is, for a cosine pulse—did the harmonics vanish near a cutoff energy of 120 eV.

In the attosecond world

Last year, Krausz and his collaborators from the University of Bielefeld in Germany paired subfemtosecond x-ray bursts with few-femtosecond laser pulses to measure the lifetime of an M-shell vacancy in krypton.[3] But in that experiment, the team didn't need to pick out the cosine bursts because the transition lasted a relatively long 8 fs. To track faster processes, controlling the carrier-envelope phase is essential.

MIT's Dan Kleppner is astonished by the ever-decreasing duration of diagnostic pulses. "When the femtosecond world opened up, I could hardly believe it. And now, here we are in the attosecond world!"

Charles Day

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