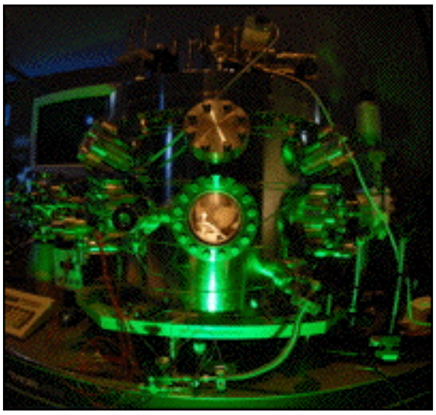
Escape from the Nucleus: Ionization via Quantum Tunneling Observed

To break free from an atom, the negatively charged electron typically has to absorb a high-energy photon, such as that from the ultraviolet (UV) or x-ray spectrum. The electron then gets excited enough to overcome the electrostatic attraction holding it to the positively charged nucleus and escapes, a process called ionization. A German-Dutch team has for the first time provided direct proof of an alternative mechanism. Powerful electric fields from a laser pulse can momentarily weaken the electrostatic bonds and enable the electron to quantum-mechanically tunnel away from the atom.



LASER PULSES lasting a few hundred attoseconds are fired into a vacuum chamber to prepare neon atoms for ionization. One attosecond is a billiionth of a billionth of one second. *Image: FERENC KRAUSZ ET AL. (www.attoworld.de)*

Leonid Keldysh, now at the Lebedev Physics Institute in Moscow, predicted the effect in 1964, and experiments have already proved that such unusual ionization can occur. But only with the advent of laser pulses lasting just a few hundred attoseconds can physicists observe the phenomenon. (One attosecond is a billionth of a billionth of a second.) Attosecond laser pulses have already made it possible to probe the motion of electrons in atoms and molecules, and improved versions will allow researchers to track electron movements that occur, for instance, during chemical reactions.

Ferenc Krausz of the Max Planck Institute for Quantum Optics in Garching, Germany, and his team describe their ionization experiment in the April 5 *Nature*. Targeting a gas of neon atoms, the group first used a 250-attosecond UV laser pulse to nudge one electron further away from the nucleus. Almost simultaneously the physicists fired an infrared pulse 5,000 attoseconds long whose electric field oscillates only a few cycles. The field weakened the electrostatic force and enabled the loosened electron to tunnel out, as quantum particles can do when confronted with a thin barrier. By increasing the time between the UV and infrared pulses in small steps, the researchers found that the number of neon ions formed rose in parallel, clearly indicating that whenever the electric field of the infrared laser pulse reached a maximum, the rate of produced ions increased as well.

Keldysh's theory of strong-field ionization has become part of many other theories, and the result is "not really a dramatic surprise," Krausz admits. But critically, "the team has shown a new way to make measurements" of electron dynamics, comments physicist Paul Corkum of Canada's National Research Council in Ottawa. And the technique could probe poorly understood processes in which electrons exchange energy with one another.

As an example, Krausz cites the "shake up" process in atoms that occurs when an energetic x-ray photon kicks out an electron close to the nucleus. While flying away, this electron could impart some of its energy to another electron, which then becomes excited and moves farther away from the nucleus. Hence, a small delay might exist between the absorption of the x-ray photon by the ejected electron and the repositioning of the second electron. The delay, Krausz remarks, "could be as little as 50 attoseconds; nobody really knows." The length of the delay is not exciting, he explainsrather the point would be whether a delay exists at all. A delay would mean that the second electron got energy from the first and was not coincidentally and simultaneously excited by the x-ray photon.

Krausz claims he has now achieved 100- attosecond UV pulses, so he may soon solve that puzzle. As the lasers improve, answers to other questions are sure to follow in the coming years, if not in the coming attoseconds.