

Measuring the immeasurable

When chemists developed techniques to peer into the heart of chemical reactions, they opened up a new world for study. Yudhijit Bhattacharjee finds out how, a decade later, the early promise has been realized.

According to the textbooks, chemical reactions are a simple business. Take some reactants, mix, supply energy if required and, hey presto, the products of the reaction are created. But when it comes to details of the heart of the process — the fleeting moments in which individual reactant molecules turn into products — the textbook accounts were, until recently, a little vague. Everything happens so quickly, often in around 10^{-12} seconds, that chemists simply could not follow the action.

The development in the 1980s of lasers capable of delivering ultrafast pulses of light changed everything. Thanks in large part to the work of Ahmed Zewail at the California Institute of Technology in Pasadena — who used the new lasers as ‘cameras’ to study the intermediate stages of chemical reactions — the first snapshots of reactions with exposure time measured in femtoseconds (10^{-15} s) were taken soon afterwards. The field of femtochemistry was born.

As the technique becomes more widely used, a wealth of findings is emerging — from detailed analyses of photosynthesis to slow-motion replays of melting semiconductors. And chemists are not resting on their laurels. The next frontier — attosecond (10^{-18} s) measurements of the movements of electrons — is already in sight, offering chemists new insights into why some reactions occur readily, whereas others do not.

Zewail made femtochemistry possible by updating an existing chemistry technique, known as optical spectroscopy. First, the substances being studied are blasted by a short pulse of laser light that contains just

enough energy to kick-start the reaction. A second pulse is then used to probe the system while the reaction is taking place. This pulse passes through the reacting substances and is analysed as it leaves. Every atom or molecule has a unique set of frequencies of light that it can absorb, so by looking for frequencies that are missing from the pulse, chemists can determine what chemical species are present, and in what quantities. Atoms or molecules can also re-emit light that they have absorbed, again at specific frequencies.

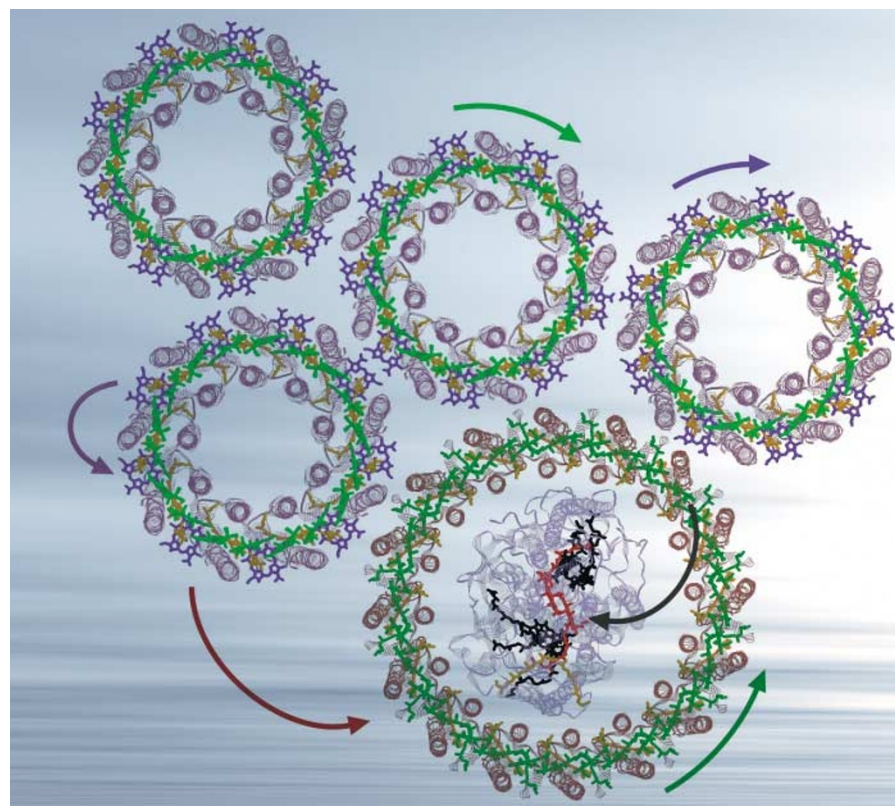
Pulse rate

By studying the absorbed or emitted light, chemists obtain a snapshot of a reaction taken as the probe pulse passes through the sample. Just as photographers use short exposures to capture fast-moving objects, so chemists need short laser pulses to study rapid reactions. A reaction can be over in 1,000 femtoseconds, so lasers capable of emitting pulses lasting a hundred femto-

seconds or less are needed to probe the details of the process.

In the 1970s, work by Charles Shank and colleagues at Bell Laboratories in Murray Hill, New Jersey, on liquid dye lasers, led to devices capable of producing pulses of just a few hundred femtoseconds. Researchers building lasers face a trade-off — the shorter the pulse, the larger the range of frequencies of light it must contain. Liquid dye lasers use fluorescent organic dyes to produce laser light. By using a range of dyes, each of which emits light of a different frequency, Shank and his colleagues were able to restrict the pulses to the very short times necessary. By the early 1980s, they had developed the technology so that pulses of tens of femtoseconds were possible¹.

In 1987, Zewail built a version of the Bell Labs laser that was capable of producing pulses of 60 femtoseconds and used it to study the dissociation of iodine cyanide (ICN) into iodine and cyanide². ICN molecules absorb different frequencies of light as the bond



Leading light: femtosecond spectroscopy was used by Graham Fleming (left) to follow the energy path of photosynthesis from the small light-harvesting complexes to the reaction centre.

TIFFANY DRESSEN



X. HU ET AL. PROC. NATL. ACAD. SCI. USA 95, 5935–5941 (1998)



Fast exposure: Ahmed Zewail used lasers as 'cameras' to study chemical reactions.

between the iodine atom and cyanide molecule stretches. Zewail took a series of snapshots of the process by sending in probe pulses at different times after the initial pulse and showed that the bond broke after around 200 femtoseconds, by which point the iodine atom and cyanide molecule had been stretched by about 5 angstroms. In itself, that finding was of limited interest, but the proof that femtosecond spectroscopy worked was a huge breakthrough. Twelve years later, Zewail was awarded the Nobel prize in chemistry.

More recently, femtosecond spectroscopy has been used to explain the remarkable efficiency of some photosynthetic reactions. The bacteria *Rhodospseudomonas viridis* and *Rhodobacter sphaeroides* interest chemists because they convert almost all of the light they absorb into chemical energy. Graham Fleming of the University of California, Berkeley, has helped piece together a detailed understanding of the chemistry that underlies this phenomenal efficiency.

The key unit in the collection of proteins that controls photosynthesis is a group of molecules, the reaction centre, that drives the reactions that convert energy from the Sun into the chemical energy needed to create organic matter. It is surrounded by a network of proteins, consisting mainly of chlorophyll. These proteins harvest sunlight, soaking up its photons and channelling their energy towards the reaction centre.

It is this channelling that fascinates Fleming and other chemists. The process starts with the absorption of a photon of light by a chlorophyll molecule. The chlorophyll gains energy from the photon, but this extra energy is rapidly transferred to a neighbouring chlorophyll molecule, which passes it on in turn. In this way, the photon's energy hops between chlorophyll molecules until it reaches the reaction centre.

Chemists suspected that the efficiency of the bacteria was due, in part, to the speed at which the energy is transferred between chlorophyll molecules. If energy is not passed on rapidly, it risks being lost as heat. Any pauses in the energy's journey to the

reaction centre would reduce the efficiency of photosynthesis.

The traditional model of how the energy is transferred, formed over half a century ago, predicted a much slower transfer than would be needed. Fleming developed the theory to produce an alternative version, complete with new predictions for the speed of the transfer. The predictions seemed plausible and, thanks to femtosecond techniques, Fleming was actually able to test them.

As the energy passes through the network of chlorophyll molecules, it changes the way they absorb and emit light. This allows the flow of energy to be detected by spectroscopy. Fleming followed the movement of the energy as it sped towards the reaction centre and showed that the jumps between molecules typically occurred in a few hundred femtoseconds³, just as his model had predicted. "Without femtosecond pulses," says Fleming, "we would not have been able to catch the excitation as it moves from molecule to molecule."

Energy drain

Fleming, together with plant biologist Krishna Niyogi, also at the University of California, Berkeley, is now tracking the flow of energy under different lighting conditions. In bright sunlight, plants reduce their light-harvesting efficiency to protect against over-excitation of the reaction centre, which can damage proteins vital to photosynthesis. Last year, Niyogi identified a protein, known as PsbS, involved in this regulation⁴. The Berkeley researchers are now using femtosecond techniques to test the idea that this protein performs its regulatory role by draining surplus energy from the chlorophylls and dissipating it as heat.

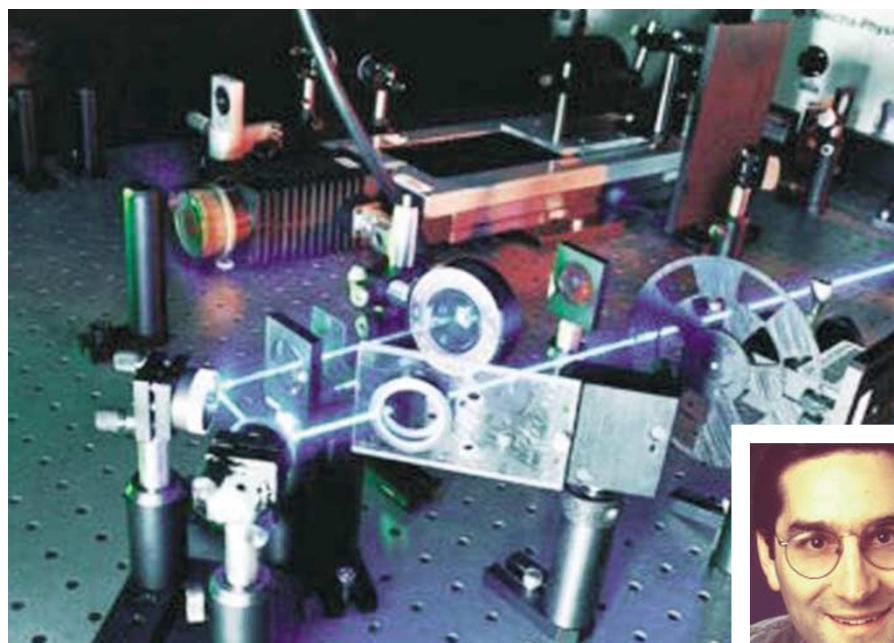
The ease and efficiency with which photo-

It's like following a hummingbird's wings — the movement is so rapid you need a fast camera.

synthetic systems channel energy towards the reaction centre has led some chemists to attempt to create artificial analogues. Researchers hope that the chemical energy generated by such a system could be harnessed to drive the synthesis of useful organic molecules. Just as naturally occurring photosynthesis was the first stage in the formation of oil and coal, artificial photosynthesis could help produce organic molecules for use as fuels.

By using long chains of polymer as light-harvesters, Benjamin Schwartz and Sarah Tolbert of the University of California, Los Angeles, have taken the first steps to developing such an artificial system⁵. The polymers were aligned in fine silica channels with their ends, which stuck out of the channels, grouped together into a bundle. Schwartz and Tolbert illuminated the bundle with visible light and used femtosecond probe pulses to follow the energy absorbed by the ends of the chains as it was channelled towards the section of the chains in the silica.

"It will be many years before we've successfully reproduced what has taken nature a billion years to design, but I do believe we will eventually be able to achieve systems that are as efficient," says Schwartz. "The time-resolved experiments are the key to determining exactly where the energy is



First light: Benjamin Schwartz (inset) and colleagues have used femtosecond lasers to study artificial analogues of photosynthetic systems.

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going and how long it takes to get there.”

Other researchers are using femtosecond techniques to reveal how genetic material protects itself against damage by ultraviolet light. Last year, Bern Kohler of Ohio State University in Columbus described how he dissolved DNA and RNA bases in water and used pulses of ultraviolet light to increase their energy⁶. He then used probe pulses of visible light to measure how long they took to fall back to their ground states.

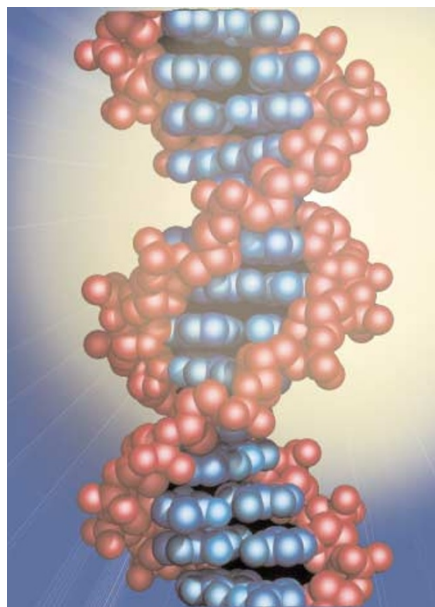
Chemists knew that the bases were able to return to their ground states very rapidly but had never studied the precise timing of the process. They suspected that the speed of the jump was one reason why nature had selected these molecules over others. Bases are more likely to react with other substances when in an excited state, so the quicker they return to their ground state, the smaller the chance of them reacting and damaging genetic material.

Kohler found that the bases do indeed lose their energy very rapidly — taking between 290 and 720 femtoseconds to do so. He also revealed that this speedy jump was made possible by the bases using the extra energy to heat the surrounding water, rather than emitting electromagnetic radiation, which is orders of magnitude slower than heat transfer.

“In a way, DNA bases serve as their own sunscreen,” Kohler says. “Photostability would have been all the more critical when life first appeared on Earth, because there was no significant ozone layer in the atmosphere to shield against ultraviolet radiation.”

Visible light is not the only kind of probe pulse that can be used. Light provides only limited information on the structure of a substance, so some researchers use femtosecond X-ray bursts as the second pulse. X-rays usually carry too much energy to excite the substance being studied. Instead they pass through the gaps between atomic nuclei. Because the wavelength of X-rays is similar to the size of these gaps, the waves are diffracted. In crystals, the regular spacing of the atomic nuclei causes interference patterns in

Femtosecond techniques have helped to reveal new classes of reaction.



Sunblock: DNA bases are their own sunscreen.

the diffracted rays. Researchers can work backwards from these patterns to determine the structure of the molecules involved.

Such techniques have helped reveal classes of reaction that researchers had previously been unaware of. Ultrafast melting is one example. When a laser pulse strikes the surface of a semiconductor, electrons in atoms at the surface absorb energy from the pulse. This energy is transferred to the thermal motion of the atoms over a period of a few thousand femtoseconds. Melting was thought to begin when the thermal energy was such that the atoms' vibrations broke the bonds between them.

But in 1999, Arlin Chin of the University of California, Berkeley, melted a semiconductor with a pulse of laser light and showed that melting began before the thermal energy had transferred to the atoms⁷. Chemists were at a loss to explain how the atoms had broken the bonds between them without gaining the thermal energy that is usually needed to do so.

Earlier this year, researchers led by Antoine Rousse of the Laboratory of Applied Optics in Palaiseau, part of the CNRS, France's national research agency, extended Chin's work. They showed that the atoms began to lose their regular structure in as little as 350 femtoseconds after the initial pulse was delivered⁸ — well before the atoms had gained the thermal energy needed to melt. The process seemed to be occurring because the electrons that absorb the initial laser

pulse can move away from the atom they were originally associated with. This reduces the forces that keep each atom fixed in position. As the atoms start to move more freely, the semiconductor enters the liquid state.

“It's like following the wings of a hummingbird,” says Rousse of the femtosecond techniques he employed. “Your eyes can't follow a movement that rapid, so you need a fast camera. But ultrafast melting is 10 billion times faster yet.”

Speed demons

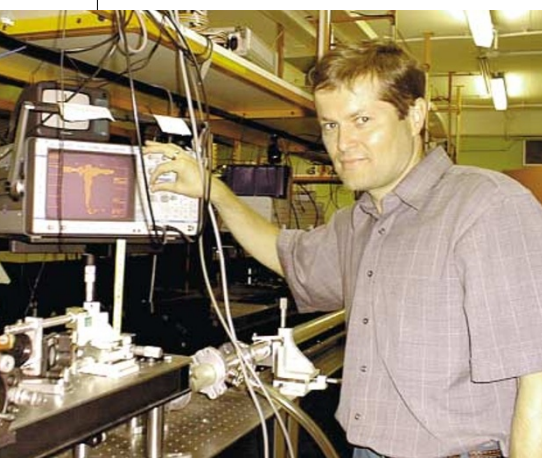
Despite the wealth of discoveries made possible by femtosecond techniques, some aspects of chemistry remain inaccessible. Whatever the probe pulse used, femtosecond techniques provide little information about the position of electrons within their orbits. According to classical theories, an electron can orbit a hydrogen atom in a fraction of a femtosecond, so pulses of just a few hundred attoseconds (10^{-18} s) would be needed to track each electron.

Some researchers believe attochemistry may soon be possible. This March, Markus Drescher and Ferenc Krausz of the Photonics Institute of the Vienna University of Technology described how they generated X-ray pulses of just 1.8 femtoseconds in length⁹. The lower limit for a pulse of visible light, defined by the duration of a single cycle of the wave, is 3 femtoseconds. But X-rays have shorter wavelengths, and pulses down to as little as 50 attoseconds are possible in principle.

If attosecond pulses can be generated, a slew of new phenomena will be open to investigation. The movement of electrons in excited molecules is one example. A molecule is more likely to react when one of its electrons is in an excited state. But the electron may fall back to its ground state before the reaction occurs. Studying the movement of excited electrons may help explain why certain reactions occur, whereas others fail to get going.

Attochemistry would be the latest in a line of advances that have redrawn the limits of the chemical sciences. Manfred Eigen, then director of the Max Planck Institute for Biophysical Chemistry in Göttingen, Germany, accepted the 1967 Nobel prize in chemistry with a lecture about his work on “immeasurably fast reactions”. Zewail, who analysed reactions over timescales a billion times shorter than Eigen, later joked about this title. If attosecond techniques do become reality, the immeasurable will have to be redefined once again. ■

Yudhijit Bhattacharjee is a writer in Columbus, Ohio.



Faster still: Ferenc Krausz believes that attochemistry could soon be possible.

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