

Zewail, Caltech's Linus Pauling Professor of Chemical Physics and professor of physics, makes movies of molecular births, weddings, divorces, and deaths with what the citation calls the world's fastest camera... "But if it weren't for the ability to glue all of these molecules together with coherence, we'd never be able to synchronize their motion."



# Coherent Thinking

by Douglas L. Smith

**Ahmed Zewail, Caltech's latest Nobel laureate, has time on his mind as well as on his screen saver.**

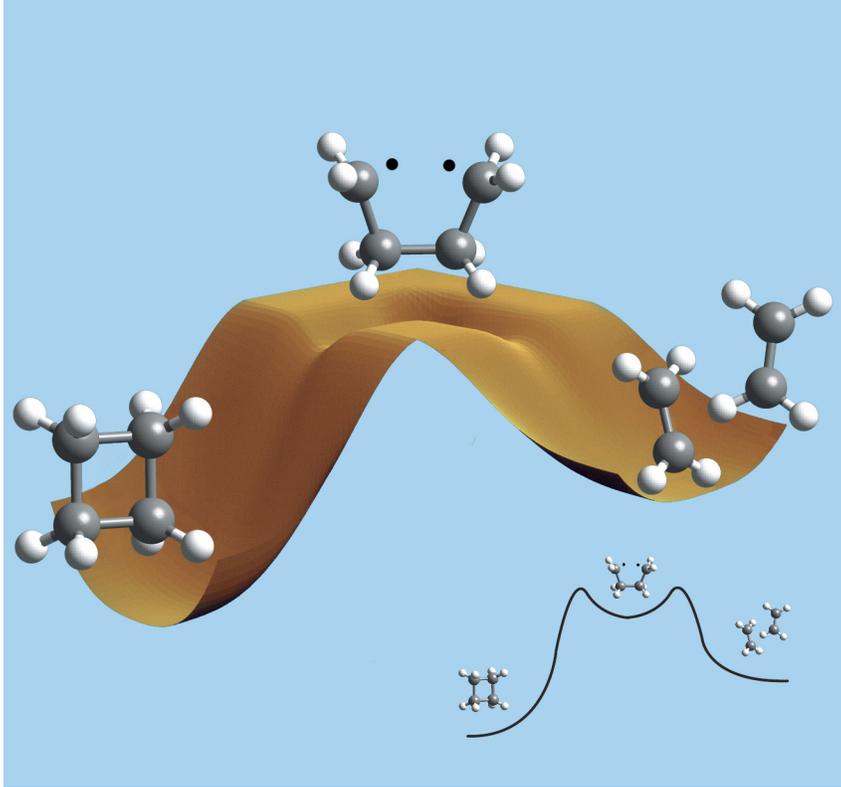
At 5:40 in the doggone morning on Tuesday, October 12, Ahmed Zewail got a phone call. But it wasn't a wrong number or a particularly ambitious aluminum-window salesman—it was the Royal Swedish Academy of Sciences informing him he had won the 1999 Nobel Prize in chemistry. The citation reads, in part, that Zewail “is being rewarded for his pioneering investigation of fundamental chemical reactions, using ultra-short laser flashes on the time scale on which the reactions actually occur. Professor Zewail’s contributions have brought about a revolution in chemistry and adjacent sciences, since this type of investigation allows us to understand and predict important reactions.” Or, as Zewail puts it, “Atoms and molecules have an enormously complex sociology, and for centuries chemists have been trying to understand why they sometimes like each other and sometimes hate each other. This love and hate is extremely important—it determines why substances can exist, and how they behave.” And, like humans, the only way to find out how they behave is to watch them in action. So Zewail, Caltech’s Linus Pauling Professor of Chemical Physics and professor of physics, makes movies of molecular births, weddings, divorces, and deaths with what the citation calls the world’s fastest camera—one with a shutter speed measured in femtoseconds. A femtosecond is a millionth of a billionth of a second— $10^{-15}$  seconds, or 0.000000000000001 seconds; a femtosecond is to a second as a second is to 32 million years. The citation continues, “The contribution for which Zewail is to receive the Nobel Prize means that we have reached the end of the road: no chemical reactions take place faster than this. With femtosecond spectroscopy we can for the first time observe in ‘slow motion’ what happens as the reaction barrier is crossed.”

This reaction barrier is generally pictured as a mountain separating two valleys. In one valley, or state of minimum energy, lie the reactants; the

products lie in the other. The reactants have to have enough energy to hike up the mountain before they can ski down the other side. These landscapes are called potential-energy surfaces, but unlike the latitude and longitude coordinates one uses to navigate cross-country, the axes of a potential-energy surface are the distances between the atoms involved in the reaction. When only two atoms are involved, the potential-energy surface becomes a curved line on a piece of paper: a two-dimensional plot of energy versus bond length. When one bond breaks and a different bond forms, the surface is three-dimensional, like a relief map, and as additional atoms get involved, the surface can occupy still more dimensions. And complex reactions may have several intermediate products in Alpine valleys scattered through a whole canton’s worth of peaks and passes.

Each summit (in two dimensions) or saddleback (in three or more dimensions) in the potential-energy surface is what chemists call a transition state—that point when the molecule is betwixt and between, no longer reactants and not yet products, its bonds, like Richard III’s physique, scarce half made up. The transition state is a razorback ridge, not a broad plateau, and molecules don’t dally there. In fact, transition states are so fleeting that before Zewail’s work they had never been observed directly, even though they had been postulated to exist since the 1930s. The best efforts to view them produced the spectroscopic equivalent of a blurry daguerreotype of a busy street.

In order to shoot bonds in sharp focus, you need a shutter speed faster than the fastest atomic motion. Explains Zewail, “A femtosecond is shorter than the period of any nuclear vibration or rotation in the molecule, so we are able to freeze the system in time. The atoms in the molecules inside you are vibrating at about a kilometer per second, and they’re so tiny that we measure their relative positions in a unit called the angstrom,



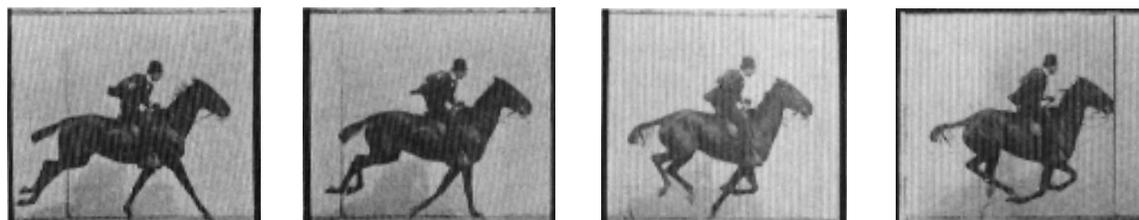
**Above:** The potential-energy surface for cyclobutane (the square molecule at left) splitting into two molecules of ethylene (right). The intermediate product (middle) lasts for a few hundred femtoseconds and is higher in energy because two of the carbon atoms each now have a highly reactive electron (black dot) that used to be half of a bond.

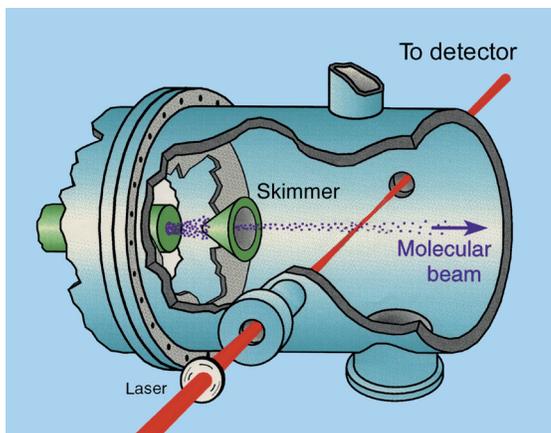
The system follows the crease of minimum energy that runs along the center of the potential-energy surface—a crease that deepens ever so slightly under the intermediate, as shown in exaggerated form in the inset.

**Below:** One hundred years, or 3,100,000,000,000,000,000,000 femtoseconds ago, Eadweard Muybridge developed a camera with a shutter speed of two-thousandths of a second, sufficient to freeze a horse in mid-stride. Muybridge had been hired by Leland Stanford, president of the Central Pacific Railroad, to settle a \$25,000 bet that a galloping horse has all four legs off the ground at some point. That's about \$450,000 in today's dollars—roughly the price of a femtosecond camera system.

which is  $10^{-10}$  meters—one ten-billionth of a meter. A typical chemical bond is a few angstroms long. If you combine these numbers, you see it takes about 100 femtoseconds for an atom to move an angstrom. So we have to be substantially faster than that to catch them in the act.” And then there’s the daunting task of getting all the molecules in step. When Eadweard Muybridge took his groundbreaking stop-motion photos of a galloping horse in 1887, one horse was ridden past a row of a dozen cameras. But each of Zewail’s photographs contains millions of molecules, as if Muybridge had run a whole herd of horses in lock step past one camera. Even when they are undergoing the same reaction, molecules don’t run in lock step, so how do you synchronize their gaits?

That’s where matters stood when Zewail arrived at Caltech in 1976 as a brand-new, untenured professor. Born near Alexandria, Egypt, he had graduated from Alexandria University in 1967 with a degree in chemistry and first-class honors. He earned his PhD at the University of Pennsylvania in 1974, where he specialized in solid-state spectroscopy and nuclear magnetic resonance, and had continued in this vein during a two-year stint as a postdoc at UC Berkeley. Lasers were pretty hot stuff back then, so he “proposed for my assistant professorship to apply some of the concepts I had learned from my other fields into lasers, and use them to probe molecules at the fundamental level.” The initial experiments, done with grad students Tom Orlowski (MS ’76, PhD ’79) and





**Above: A look inside a molecular beam's vacuum chamber. The carrier gas shoots out of a pinhole in the end of the green pipe at left, and immediately expands in all directions. After traveling a couple of centimeters, the gas cloud hits a skimmer, which is essentially a funnel with a pinhole at its point that shoves aside all the straying molecules. The molecules that survive the skimmer have very little sideways velocity, so when the molecular and laser beams cross in another few tens of centimeters, all the molecules are on essentially parallel paths.**

**Above, right: The hardware.**

Dan Dawson (MS '78) and undergrad Kevin Jones (BS '77), proved that short laser pulses (and in those days, short laser pulses were measured in nanoseconds, or billionths of a second—an eternity in his lab today!) could excite simple or even complex molecules into so-called coherent states, and that such coherence could be detected during their spontaneous decay. In other words, even though each individual molecule in the sample was zipping around on its own course, banging into its fellows and tumbling like an X-wing fighter that's taken a hit, there were some spectroscopic phenomena in which a huge percentage of them acted together. If shot with a sufficiently brief laser pulse, they would shed the excess energy in a coordinated fashion. The chemistry faculty was sufficiently impressed to give Zewail tenure in less than two years—an ultrafast reaction in its own right.

"After doing that," Zewail recounts, "I was interested to see whether we could look, not at perturbations between molecules, which is what we had done with these experiments, but at what coherence goes on *inside* complex molecules. Why not try to isolate these molecules from the rest of the world by doing what's called molecular beams? So we built our first molecular beam in '79." A molecular beam is just what its name implies—a beam of molecules enclosed in a vacuum chamber that looks like a capped-off segment of stainless steel sewer pipe. You vaporize your sample and suck it up into a stream of an inert "carrier" gas

such as argon, and squirt the gas through a pinhole into the vacuum chamber at right angles to the laser's path. The carrier gas dilutes the sample so that, although the laser is exciting millions of molecules at a time, the molecules don't collide with one another. The gas also expands when it enters the vacuum, accelerating the molecules to supersonic speeds, and, paradoxically, cooling them. An isolated molecule has a fixed kinetic-energy budget, so the extra energy invested in speed has to come from the molecule's rotational- and vibrational-energy accounts. The energy overdraft protection plan kicks in automatically, leaving the fast-flying molecules flat broke and plunging their temperatures to within a few tens of degrees of absolute zero. This is a vital first step to establishing coherence, because the bankrupt molecules can afford to live in only the lowest-energy rotational and vibrational states, imposing a significant degree of order on them already.

"I knew *nothing* about this technology," Zewail confesses. "But I had two *wonderful* students, Bill Lambert [PhD '83] and Peter Felker [PhD '85], who were willing to take on this new vision. They really started from scratch." Molecular-beam technology is pretty standard nowadays, but back then trying to meld a molecular beam and an ultrafast laser into a workable apparatus posed huge technical challenges. But though the Techers were molecular-beam neophytes, Lambert explains, they had "a significant advantage in having a close relationship with Spectra Physics [the leading manufacturer of high-speed lasers], which provided equipment in the initial stages of production and development to our group at a substantial discount. This enabled us to perform experiments everyone in the field wanted to perform before anyone else reasonably could."

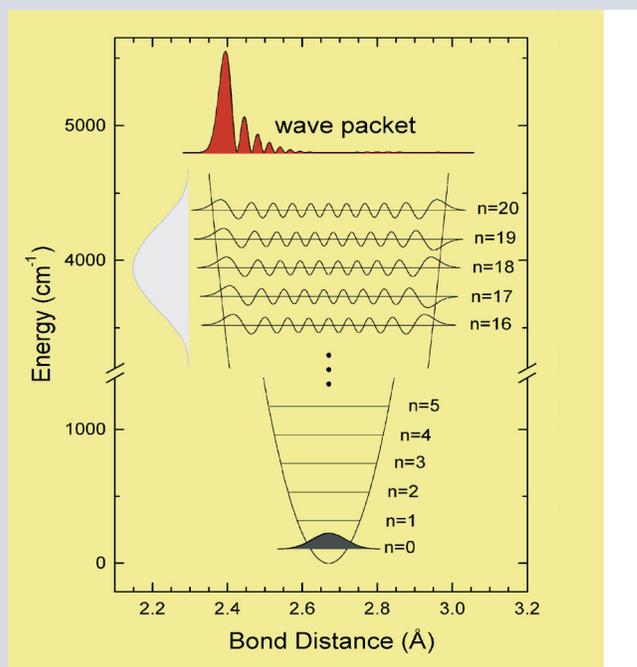
This experiment called for a large but well-chosen molecule, says Zewail. "We chose anthracene as our molecular guinea pig because its



In the quantum world, waves can be particles and particles—even molecules!—can be waves as the occasion demands or the whim takes them. The wave's amplitude at any point is a measure of the likelihood of finding the molecule there. Each vibrational state has a different wave function (here labeled  $n = 0$  to  $20$ ) that reflects the probability of finding the molecule in that state at that location; in this example of a two-atom molecule, it's the probability of finding the two atoms separated by a given bond distance. Each state's probability wave extends from wall to wall of the potential-energy surface (the parabola), meaning that, in the case of state  $20$ , there are 21 bond distances one would expect to see—count the crests and troughs (yes, the troughs matter, too; they have a nonzero amplitude). So any quantum mechanic could tell you that a photo of the molecule in that state would be blurry, because the atom would show up equally at all 21 of those bond lengths—it would be naive to expect the atom to be a ball on a spring that moves through one bond distance at a time as it bounces back and forth between the walls. But if you want to make a movie of a bond breaking, a ball on a spring is exactly what you need to be able to see.

The sum of all these wave functions is the overall probability wave for the molecule in all of its states. Normally, the component waves are out of step, but when they're coherent, they interfere with each other. Where crest matches crest or trough matches trough, you get a big amplitude; where crest matches trough, you get zip. It's like striking two adjacent keys on a piano—the sound comes and goes in “beats” as the waves alternately add to and cancel each other. (These oscillations, known as quantum beats, are what Lambert and Felker were seeing.) When all the molecules are coherently excited into just a few states, as shown by the gray bell curve, something truly remarkable happens—the sum of these states, called a wave packet, is now “localized.” It has a nonzero amplitude in only a very small region, and the molecules—all of them—have to be there. And if you watch this wave packet over time, you'll see it travel back and forth from wall to wall, just like that ball on a spring that quantum mechanics says you can't see! (This would do you no good if each molecule's wave packet had begun moving at a slightly different time, as you'd *still* get a blur. But the laser pulse synchronizes all the molecules, lining up their toes in the blocks and firing the starter's pistol.)

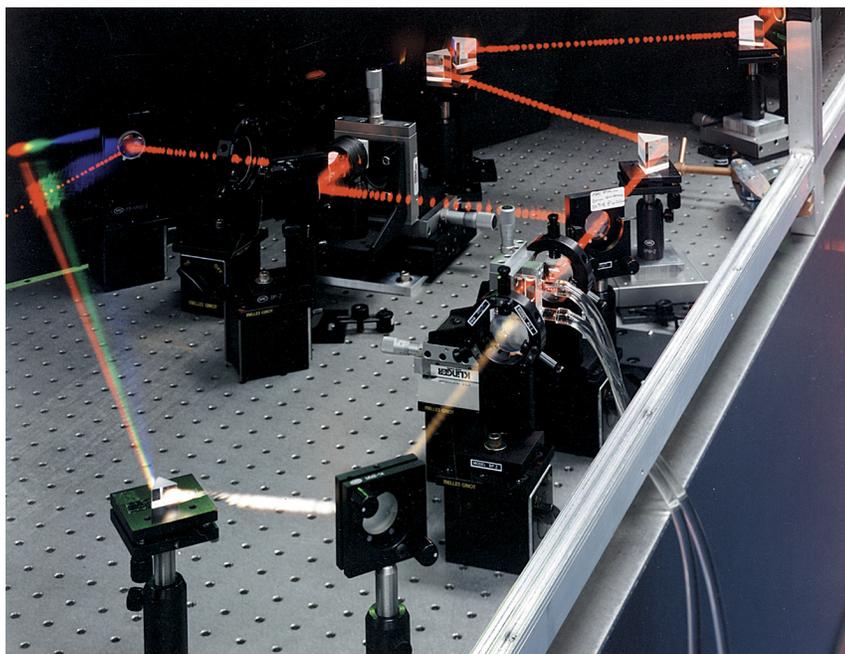
The same story holds true for the molecule's rotational states.



spectroscopy gave us a hint that energy redistribution might be happening in the molecule. Also, the frequencies of all its vibrational modes were well known.” A laser pulse tuned to one of those frequencies excited the molecules into that vibrational mode. Then the researchers counted the picoseconds—we're down to trillionths of a second, now—until the molecule got rid of that extra energy by fluorescing. Anthracene is a big, flat molecule consisting of three hexagons fused edge-to-edge, so there are hundreds of ways it can vibrate. For example, if you picture it as a bat in flight, it could stretch out its wingtips, or flap them, or scull them forward and backward, or curl the edges up and down, and it can do all these things with the wings either alternating or coordinating their motions. And then there's the body, which can move, too. These states require roughly the same energy, so, says Zewail, “if, on a short time scale, we deposited energy into a big molecule isolated from the rest of the world, could we see how the energy will go around within the molecule? This was a hot area—lots of conjectures, inferences, and claims.”

Everyone expected to watch the fluorescence decay smoothly as the energy leaked away, with each molecule dumping its energy into a randomly chosen state—a little here, a little there, but not a whole awful lot to any one state. And that's exactly what happened, except that suddenly, some picoseconds later, the fluorescence came back! It spiked and then disappeared again... and again... and again... as many as nine times. Says Zewail, “Everybody knows we are born, we die, and that's it. But if all of a sudden somebody is coming back from the dead, reincarnated like Shirley MacLaine says, it would be an incredible result. And, of course, some people would be skeptical.”

“I was in Paris or somewhere to give a talk, and I called Peter and Bill in the lab, and I said, ‘What's new? How's the experiment going?’ because we had been trying really hard to get this experiment to work, and they told me, ‘Well, we're seeing something that's really *something*. It's not decaying—it's *oscillating*.’ And this was incredible. This was indeed the door-opening observation.” What this meant was that all the energy was moving into just one other state, and from there back to the original state. Such oscillations were known in atoms and small molecules with a handful of states, but unexpected in large molecules with a profusion of states. Proving it meant finding the other state into which the energy was going. Sure enough, when the other frequency was found, it was dark at first, but picoseconds later it lit briefly, faded, then returned. Comparing the signals verified that one rose as the other fell. It's like that toy with the two magnetic propellers—you set one spinning, and the magnets in its propeller tips tug on the magnets in the other one's tips. The second one starts twitching as the rotational energy trickles



**Above: Femtosecond laser pulses on parade.**

over, and soon both are spinning, until all the energy has been sucked out of the first one and it stops. But not for long—as the second propeller’s tips tug on it, the energy starts to slosh back. (A somewhat more rigorous description of molecular coherence is given in the box on the previous page.) Zewail explains, “We saw a coherent cycle, with energy going back and forth between a very select number of vibrations. And even though we had a million molecules, we were observing their behavior as if they were one molecule because we were using such short pulses.” So all the mole-

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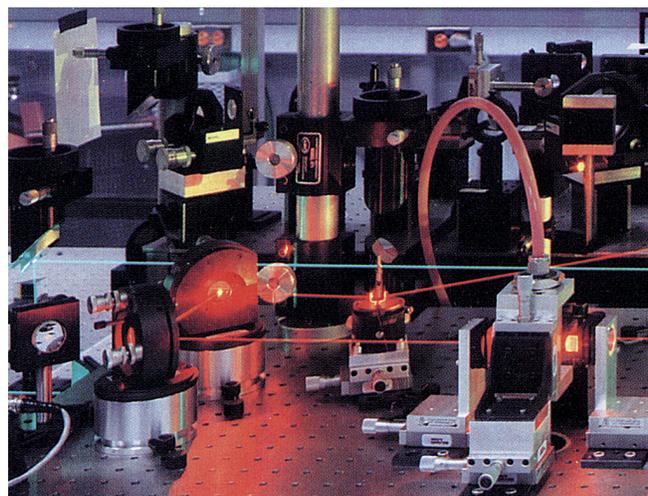
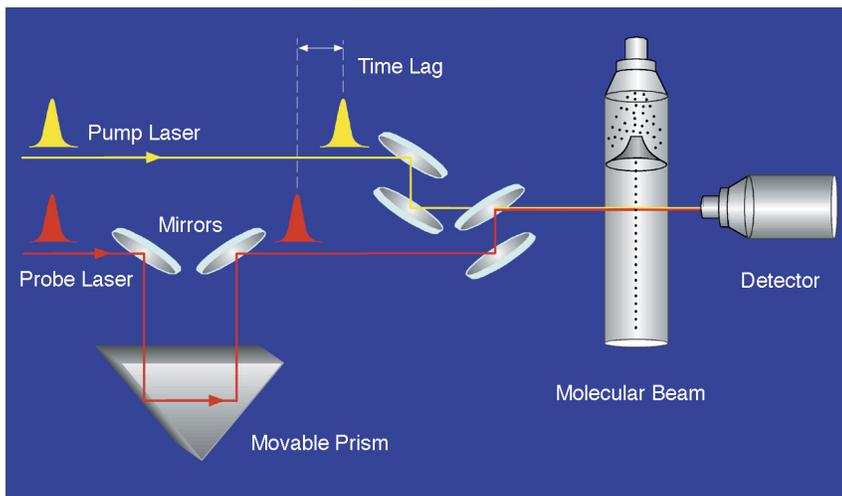
cules would choose to, say, flap their wings, then curl their wingtips up, and then flap them again—a regular chorus line of molecular bats!

Nobody knew it then, but this demonstration of intramolecular coherence was the key to making femtochemical movies. It implied that, under the right conditions, a horde of complex molecules could march in lockstep from a common starting point for a considerable length of time. Thus, a snapshot of any one of those molecules represented them all, and a series of pictures of different molecules taken at different times, when arranged in order, truly was equivalent to a time-lapse movie

of a single Joe Average molecule. The inverse-Muybridge problem of synchronizing the gaits of a herd of horses running past a single camera had been solved.

“So then,” Zewail continues, “we said, well, if we can see the vibration, would it be possible to observe the molecule’s rotational motion in real time? I had another brilliant experimentalist by the name of [John] Spencer Baskin [PhD ’90], who is now a senior research fellow in my lab. And, in 1986, Spencer and Peter published the first experimental observations of coherent rotational phenomena in isolated molecules, using a molecule called stilbene.” When the molecules go supersonic and lose their excess rotational energy, they don’t all wind up in the same state. Some will be tumbling end-over-end; some will be rolling around their long axis, like a barrel going down a hillside; some will be spinning like tops. Most will be doing all three of these things, but at different speeds, and, of course, no two of them will be in step. When you hit them with the laser, it punts them into an excited state where they will fluoresce, but it doesn’t change the way they’re rotating—that is, if they’re tumbling it won’t set them spinning, nor will it make them tumble faster. But if the laser is vertically polarized, it will only excite molecules that happen to be vertically aligned at the moment the laser is fired. The molecules rotate out of alignment immediately, of course, and an ordinary fluorescence spectrum is featureless. But slap a vertically polarized filter on the detector, and behold! oscillations. “Every time the faster-rotating molecules caught up with the slower ones, they all came back into phase, and we saw a peak,” Baskin explains. “The peak could go up to almost its original height, and the coherence was maintained for nanoseconds.” Repeating the experiment with horizontal polarization gave the same result, only 90 degrees out of phase. And with the establishment of rotational coherence on top of vibrational coherence, the creation of a composite molecule was complete. “I was so thrilled, so excited,” Zewail recalls. “When we started this work, most people did not appreciate the importance of molecular coherence. The chemists thought it was just physics, and some even suggested that I should be doing chemistry! But if it weren’t for the ability to glue all of these molecules together with coherence, we’d never be able to synchronize their motions—one guy would want to start earlier, one later, and so forth. So it immediately became clear that we had to push the time scale further.”

Fortunately, lasers were getting faster too—Spectra Physics had just developed a pulse compressor that would deliver a 400-femtosecond burst. But the pulses were getting so truncated that they didn’t have many photons in them, so every last one was precious. A couple of decent dust motes could scatter the beam, which was



**Above: The pump-probe concept. The pump pulse takes a more direct route to the detector, while the probe pulse takes a roundabout path and arrives later. Moving the prism toward or away from the mirrors adjusts the lag time. Above, right: The reality, of course, is somewhat more complex—and this is only a portion of the optical apparatus.**

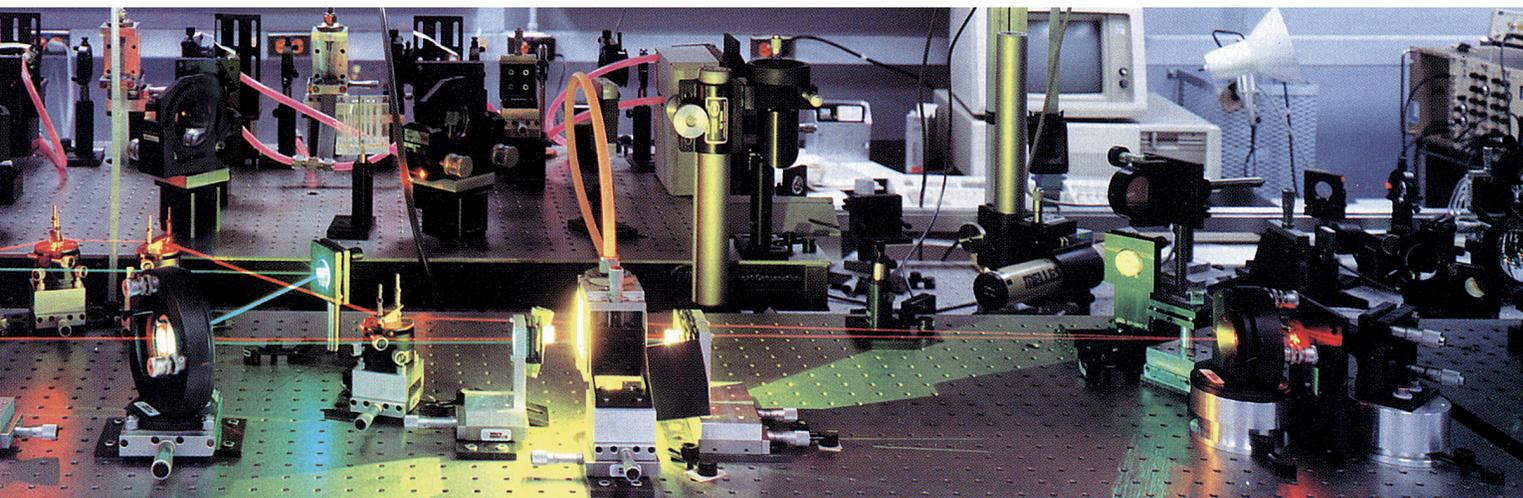
about the diameter of paper-clip wire. And an air current—from something as innocuous as a grad student crossing the room to turn off the lights—could cause the laser to twinkle like a distant star. So sliding plastic panels, not unlike patio doors, were hung around the optics, and anyone entering the lab has to don stylish blue paper booties before crossing the threshold, while the lab is further protected from dust by sticky white plastic welcome mats—flypaper for your feet.

The lasers had also outpaced the electronics—before a time signal could travel by wire to the detector, the experiment would be over. So while Baskin and Felker were nailing down coherence, postdoc Joe Knee and grad student Norbert Scherer (PhD '89) were pushing forward with another technique the lab had been developing that harked back to Zewail's early nuclear magnetic resonance training. NMR uses one radio pulse to put a molecule into a desired state and then a second one (sometimes more) to monitor the response. The new method used two laser pulses, or, rather, one pulse split in two by shining it through a partially silvered mirror. The first part, called the pump pulse, started the clock: it triggered the reaction by twanging the molecule at the frequency of the bond to be broken, pumping it to bursting. The second part, called the probe pulse, was tuned to the frequency of the bond to be observed and was detoured through a forest of lenses and prisms to arrive a predetermined number of femtoseconds later, photographing the reaction in progress. Says Zewail, "The beautiful thing is that the speed of light is so huge— $3 \times 10^8$  meters per second—that if we move a distance of one micron [a millionth of a meter], we can create a delay of 3.3 femtoseconds."

In most places, time is money, but in the Zewail lab, time became distance. An experiment started by adjusting the second path until both pulses arrived at the sample simultaneously (in other words, making the paths exactly equal in length),

setting time-zero very accurately and recording the molecules' initial configuration. Then, a precision-driven worm gear eased a mirrored prism just a skosh farther away on the second path. Thirty microns equals 100 femtoseconds, which was about the resolution of that first experiment, done in 1985. This wasn't yet fast enough to salami-slice the transition state, but sufficed for watching the product appear. For cyanogen iodide (ICN) breaking into an iodine atom (I) and a cyanide radical (CN), the very first snapshot revealed significant cyanide buildup, and the show was over in six frames. (As a side note, Spectra Physics' first 400-femtosecond pulse compressor was actually delivered to former Zewail grad student Duane Smith (PhD '81), who was by then a professor at Purdue University. The company told Zewail it would take months to build another one, so he got on the phone with his protégé and talked such an exciting game that Smith loaned him the compressor and came out to Pasadena for two weeks to join the fun.)

How fine you can slice time also depends on how narrow you can make your pulse. By 1987, the next-generation compressor could deliver 50-femtosecond pulses. The way the math works, you can see time differences of about one-fifth the pulse width, making 10-femtosecond resolution a reality. The race against time was over, and the experimentalists had won. (The subbasement room in which the apparatus lives, 047 Noyes, housed Linus Pauling's X-ray diffraction lab in the late '60s—a coincidence that Zewail, who holds the Pauling Professorship, finds satisfying.) Grad student Marcos Dantus (PhD '91) and postdoc Mark Rosker (BS '81—he went to Cornell for his PhD, but just couldn't stay away) went back to the ICN dissociation reaction, snapping away at 10-femtosecond intervals, fast enough to record a dozen or so frames of the I—C bond breaking, little by little: the first time such a thing had ever been witnessed in real time. "Those



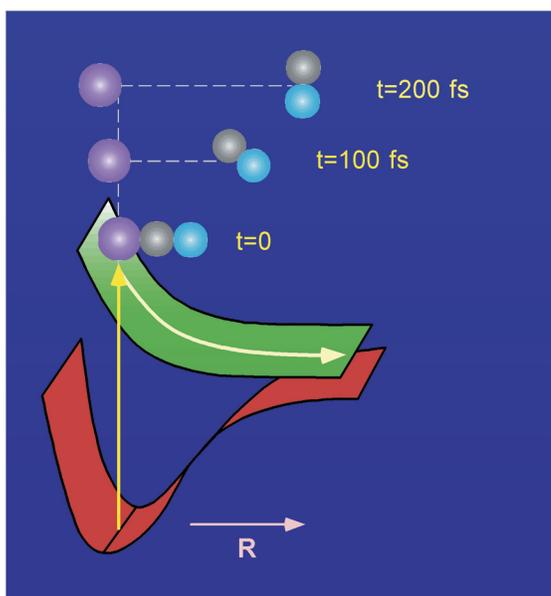
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were thrilling moments,” Zewail recalls fondly. “Marcos threw himself into everything he did, no matter what it took. And Mark was a gifted experimentalist who brought the Techer tradition back to our lab.” And again, the faculty took notice—upon graduation, Dantus won the Clauser Prize, which is awarded annually “to the PhD candidate whose research is judged to exhibit the greatest degree of originality as evidenced by its potential for opening up new avenues of human thought and endeavor as well as by the ingenuity with which it has been carried out.”

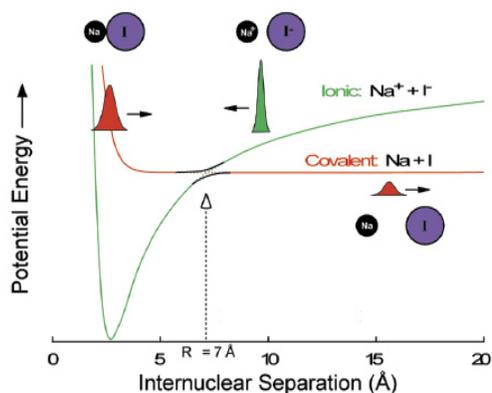
These slow-motion movies are composite pictures in more ways than one. The exact frequency that a bond absorbs depends (among other things) on the distance between the atoms. So you set the probe laser to a frequency that corresponds to some distance, and then march through a complete set of, say, 150 delay times to see when that particular bond distance shows up. Then you reset the probe

to a slightly different frequency and do it all again. Once you compile all the appearance and disappearance times for all the bond lengths into a single data set, you can see the bond stretch till it snaps. And snap it does—ICN falls apart in a mere 200 femtoseconds. (See *E&S*, Spring 1988.) There’s an additional subtlety to the ICN experiment: the frequency a bond absorbs also depends on the mass hanging from each end of the bond, so Dantus and Rosker tuned in on the free CN fragment, whose spectroscopy is a well-read book. The iodine atom’s mass drags the CN vibration to a slightly lower frequency, which rises to the free fragment’s frequency as the iodine atom loses its grip.

Not every dissociation is so fast. Postdoc Todd Rose and Rosker next assaulted molecules of sodium iodide, a simple molecule that Zewail calls “the drosophila of our field.” Sodium iodide, an experimental system that was a favorite of Pauling’s, exists in ionic form when left unmolested. When neutral sodium and iodine atoms approach one another to within 6.9 angstroms, the greedy iodine steals an electron from the sodium and becomes negatively charged, leaving the sodium ion with a positive charge. The two ions cling together electrostatically in a deep, steep energy valley at a bond length of 2.8 angstroms. But it’s also possible for the two atoms to share the electron in what chemists call a covalent bond, whose potential-energy surface lies at a higher elevation and has only one sidewall, like a ledge on the mountain’s face. At distances of greater than 6.9 angstroms, the covalent potential-energy surface is actually lower in energy. In other words, the ionic and covalent potential-energy surfaces—parallel universes, if you will, that occupy the same space—intersect at that distance. And, as any viewer of any incarnation of *Star Trek* will tell you, where parallel universes cross, there’s a portal from one to the other. In other words, the *real* potential-energy surface—the solid ground on

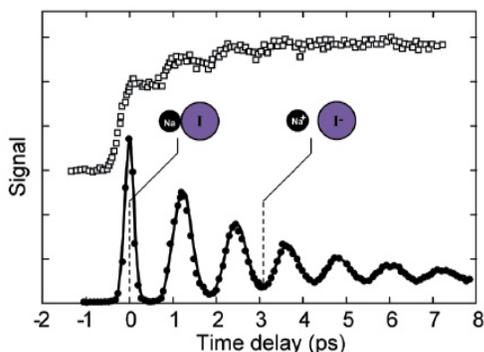


**Left:** The ICN breakup reaction’s potential-energy surface (red) bottoms out at the normal I—C bond distance. The pump laser kicks the molecule onto a higher-energy surface (green), down which it slides as it breaks up.



**Above:** Sodium iodide's ionic potential-energy surface (green) and covalent potential-energy surface (red) intersect, forming low- and high-energy surfaces. The pump laser excites the system onto the high-energy surface and kicks the atoms apart. With every outbound crossing, the excited wave packet risks missing its turn and remaining covalent, in which case the two atoms will fly apart.

**Right:** The pump laser blasts a fair number of atoms apart at time zero, as the data plotted in open squares shows, and their number increases with each cycle. The solid circles are the number of covalently bound molecules whose bond length is 2.8 angstroms.



which the system hikes—is ionic at short range and covalent farther out. The pump laser punts the bond onto the unused, high-energy portions—covalent close up and ionic afar—that float above the low-energy landscape where the system normally lives. The laser also sets the atoms flying away from each other, and as they pass the magic 6.9 angstrom mark, the iodine snatches the electron, reverting to ionic form. As anyone who has ever pulled polyester socks out of the dryer knows, charges don't like to be separated, and the femtoscale version of static cling starts pulling the atoms back inward. They whoosh together again, and at 6.9 angstroms the iodine coughs up the electron. Says Zewail, "For the first time, we could see a chemical bond transforming in real time from covalent to ionic, covalent, ionic, covalent, ionic, covalent, ionic, covalent, ionic—in this case, by the way, they were in love for about nine or ten cycles before they divorced each other at the end." With each cycle comes a chance that the outbound system would stay on the covalent potential-energy surface beyond the crossover point, in which case the two electrically neutral atoms would part company forever. The sodium-iodide marriage took about 8 picoseconds to fall apart—a long-term commitment on the atomic scale, if not the human one.

Meanwhile, across the hall, Scherer, grad student Lutfur Khundkar (PhD '88), and the late Richard Bernstein of UCLA were shooting an even tougher assignment: an atom of hydrogen and a molecule

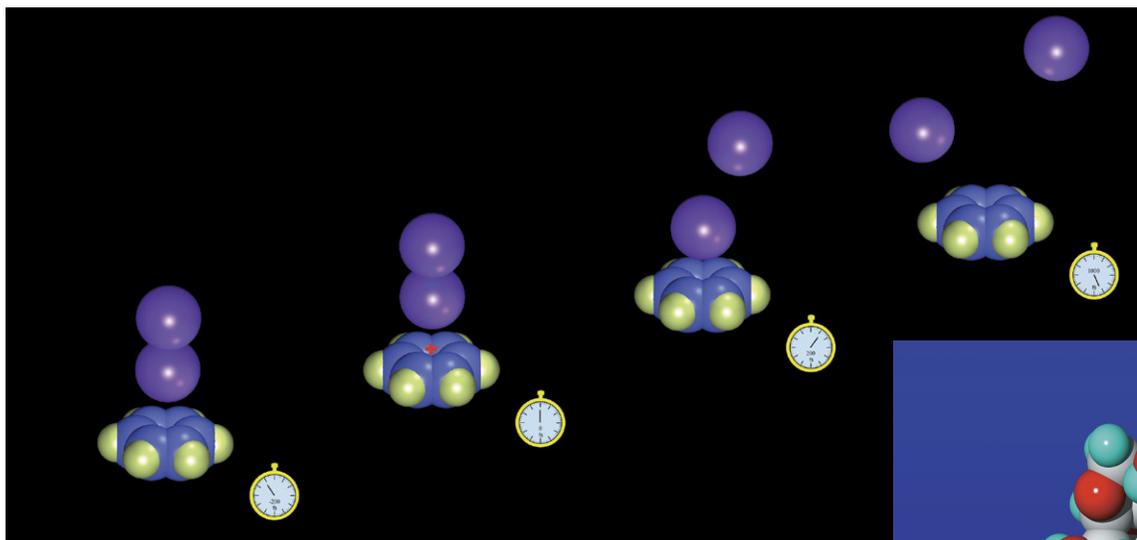
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ionic at short range and covalent farther out.

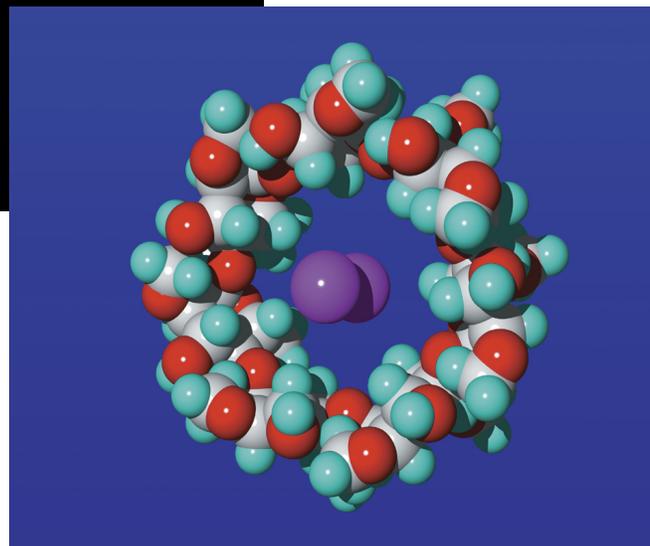
of carbon dioxide going to a hydroxyl radical and a carbon dioxide molecule ( $\text{H} + \text{CO}_2 \rightarrow \text{OH} + \text{CO}$ ). (Bernstein was a longtime collaborator of Zewail's and a familiar face at Caltech, having once been a Sherman Fairchild Scholar. His important contributions to femtochemistry were cut short by his untimely death in 1990.) Watching a molecule fall apart is all well and good, and a lot of important chemistry happens that way. But how do you bang two molecules together so that they will react? Most collisions are fruitless—the atoms just ricochet off each other. To react, they need to be in just the right orientation, and have to hit each other hard enough to stick. And how do you start the clock consistently with each fresh pair of molecules? Unlike Muybridge's camera, there are no trip wires for the inbound molecules to cross. Fortunately, as Curt Wittig showed at USC, if you shoot a mixture of carbon dioxide and hydrogen iodide (HI) into the vacuum chamber, when the two gases go supersonic and lose energy, some of the molecules will pair up into loosely bound clusters that put the atoms in the proper relative positions at a fixed separation, ready to be zapped with the pump laser.

Now that one bond (in this case, the H—O) is forming while another (C—O) is breaking, we get into questions of sequence and timing. Do both happen at once? Are there intermediate products? The researchers discovered that once the H had collided with the O, the atoms clung together for a few picoseconds as they climbed the energy mountain leading to the H—O bond. Then the intermediate HOCO hung around, quivering like a Jell-O mold, for another picosecond or so as the excess collisional energy worked its way into the C—O bond in order to blow it apart. The exact timing could then be compared to the detailed quantum-mechanical predictions numerous researchers were making from first principles—a rigorous test of the theory.

Femtochemistry took off in the 1990s. Zewail's group immediately moved to the next level of complexity—organic chemistry, the chemistry of carbon atoms and therefore of life. The group started with simple organic molecules—the cyclo-



Some of the worlds of femtochemistry. Organic, above: When you hit a benzene-iodine complex with the pump laser, an electron jumps from the benzene molecule (+) to the iodine molecule (-). The iodine molecule promptly falls apart, even if the electron has already leapt back to the benzene. Supramolecular, right: This Christmas wreath—the holly berries are oxygen atoms—is a nanocavity made of sugar molecules in which an iodine molecule nestles all snug, and in which reactions can be catalyzed. Electro, lower right: A simple stand-in for hemoglobin, a big, complex protein that carries oxygen in your blood.



This version is used to study how oxygen binds, which is also relevant for generating electricity in fuel cells. Theoretical, below: Pyridine's six-membered ring can crumple in many ways that can be predicted by quantum mechanics and tested and observed by femtochemists. The excited wave packet can follow the green arrow into a box canyon and shed its excess energy by fluorescence, or it can fall through the conical intersection back to the lower potential-energy surface and follow any number of reaction routes, two of which are shown by the red and yellow arrows.

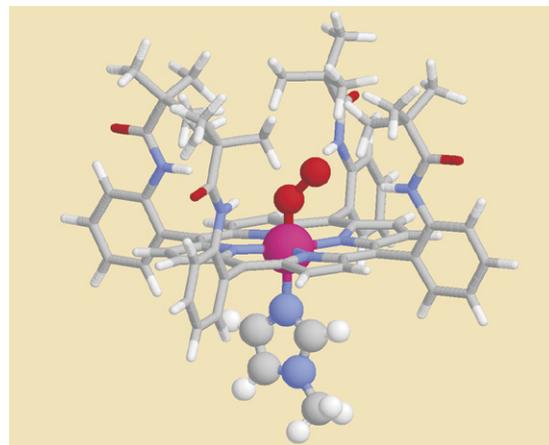
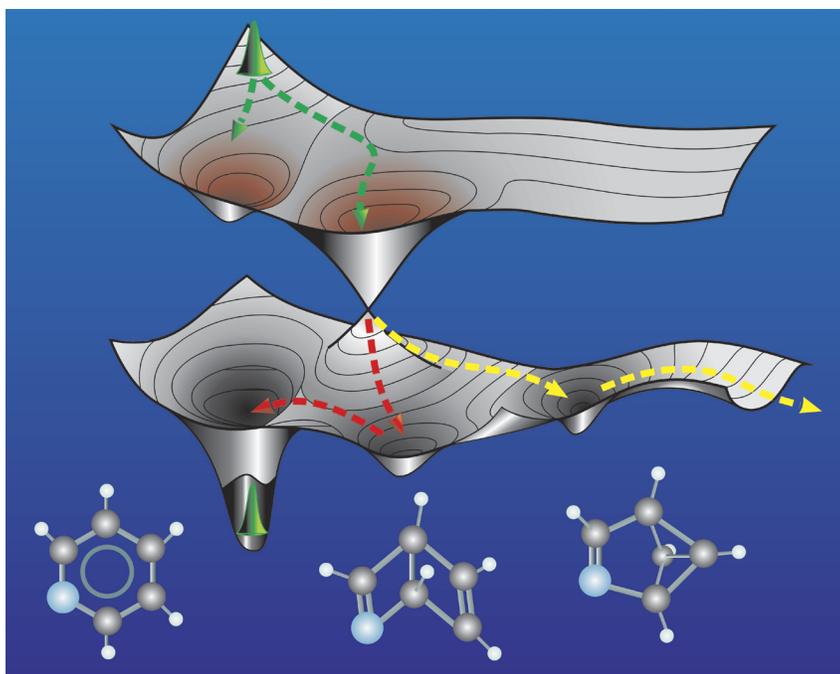


Illustration credits, clockwise from top: Dongping Zhong, Mirianas Chachivilis, Spencer Baskin, Dongping Zhong.

Zewail takes great pride that his entire professorial life has been spent here, so the prize is truly a Caltech one.... He takes even greater pride in being at the same institution where his hero, Linus Pauling (PhD '25), did his own Nobel Prize-winning work on the nature of the chemical bond.

butane reaction pictured earlier—and soon worked their way all the way up to DNA. (Jacqueline Barton, the Hanisch Memorial Professor and professor of chemistry, and Zewail are watching electrons fly down a DNA strand. DNA is a potentially good conductor of electricity, and this attribute may be important biologically.)

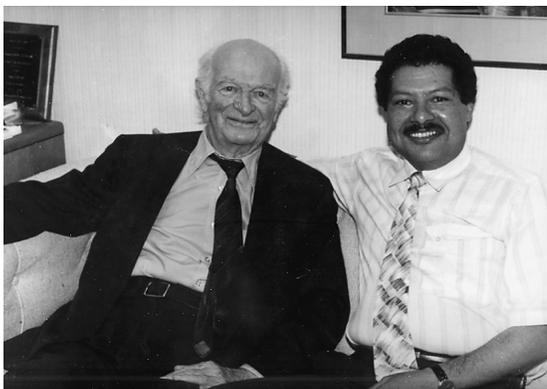
And the Zewail lab continues its tradition of figuring out how to apply instrumental methods from other fields, bringing in such techniques as mass spectrometry. Organic molecules are complex enough that a reaction starting with a given molecule will often proceed by several routes at once, giving you a family of similar looking products that absorb and emit similar frequencies of light. But mass spec, as it's called, separates molecular fragments by their mass-to-charge ratio, allowing you to discriminate between two variants that differ by as little as one hydrogen atom. A fancier version measures the arrival time, energy, and spatial orientation of each piece—vital clues for reconstructing the molecule's history. Dongping Zhong (PhD '99), who also won the Clauser Prize upon graduation and is staying on as a postdoc, developed these applications.

Chemical theory comes in for its fair share of scrutiny as well, because femtochemists can make very stringent tests of theoretical predictions by using one of those complex molecules that can follow many reaction paths, and comparing what actually happens to what the theory says should occur. Says Zewail, "In the world of complex reactions, the initial efforts of Jennifer Herek [PhD '96], Soren Pederson [MS '94, PhD '96], and postdoc Luis Bañares, culminating in the work of postdoc Eric Diau, have taken the work to a whole new level."

There are now six Femtolands, as Zewail's laboratories are affectionately called, in which, over the years, a gross of grad students, undergrads, and postdocs have studied a hundred or so reactions from all branches of chemistry. And the outside world followed right behind. As the

Nobel citation said, "Scientists the world over are studying processes with femtosecond spectroscopy in gases, in fluids and in solids, on surfaces and in polymers. Applications range from how catalysts function and how molecular electronic components must be designed, to the most delicate mechanisms in life processes and how the medicines of the future should be produced." Following the announcement of the Nobel Prize, the Institute for Scientific Information, which uses how often a researcher's papers are cited in their peer's publications as a proxy for how influential the cited work is, announced that femtochemistry had been footnoted 50,000 times since its birth.

One of the projects the Nobel committee singled out had to do with stilbene, which has two benzene rings at opposite ends of a double bond. Double bonds don't spin freely, so the rings are locked into position—if you think of your shoulders as being the double bond and a tennis racquet in each hand as the benzene rings, you can hold both racquets up (what chemists call the *cis* configuration), or hold one up and one down (the *trans* configuration). However, zinging the right laser pulse at the bond unlocks it and flips the rings. Pederson and Bañares were studying *cis*-stilbene in 1992, and found that not only do the shoulders move, but the wrists turn at the same time, and the entire process is coherently complete in 300 femtoseconds. Work at UC Berkeley by Richard Mathies and Charles Shank on biological molecules with a similar double-bonded structure showed that retinal, a light-sensitive pigment in the eye, undergoes a similar reaction with 70 percent efficiency in 200 femtoseconds as the first step in transforming a photon of light into a nerve impulse. The fact that the reaction happens so quickly and so efficiently (a vital attribute for good night vision!) indicates that the incoming light goes straight to the double bond rather than being spread throughout the molecule—a theme that runs straight back to those early coherence experiments. It's identical in concept to sodium

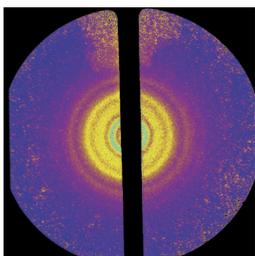


**Above: Professor Linus Pauling and the Linus Pauling Professor.**

**Below: A picosecond electron diffraction image.**

**When the electron beam hits the atoms in a molecule, the electrons scatter in all directions.**

**The bullseye pattern shows the electron density at different angles, from which you can back-calculate where the atoms must have been to produce that distribution.**



iodide—the wave packet that represents the twisting motion of the double bond is going back and forth between two states. Other researchers tell the same story about photosynthesis, the process by which plants harvest energy from sunlight. And there's even talk about using lasers to steer chemical reactions—for example, coaxing a drug precursor to fall apart in just the right way to give a 100 percent yield of the drug. Laser-selective chemistry has become a hot field in many labs, and Zewail, who anticipated the field in a paper written in 1980, expects to see substantial progress within a decade or so.

But Zewail has his eye on The Next Big Thing: “Can we actually take a direct structural image of a molecule as it undergoes these transitions, using femtosecond electron diffraction? Once we break a bond here or a bond there, how does the architecture of this molecule change with time? This is a dream I have shared with some members of my group since 1991, and it has become a major effort lately. Just this year, postdoc Jianming Cao and grad student Hyotcherl Ihee showed for the first time that we can actually see the chemical structure of the entire molecule in a simple model system on a picosecond time scale, and postdocs Boyd Gibson and Vladimir Lobastov and grad student Ramesh Srinivasan are also involved in developing the methods and apparatus.” Spectroscopic techniques focus on one bond at a time, and even the most patient grad student would balk at the prospect of looking at every blessed bond between the several thousand atoms of your average small protein. But a diffraction pattern, in principle, gives you the three-dimensional location of all the atoms in the molecule, regardless of its size, and it gives them to you all at once—a true snapshot! The setup uses the usual femtosecond pump laser to start the clock. However, the probe, after going down its variable-length path, is focused on a photocathode, which emits electrons when hit by light. This adds a mutually perpendicular electron beam to the

intersection of the pump beam and the molecular beam. “Just like a chest X ray,” Zewail says. “When we look at a molecule’s diffraction pattern we can ‘see’ the structure. Our ultimate goal is to see how the atoms move as they perform a biological function. You can imagine watching a protein, for example, moving around as it catalyzes a reaction, or as it recognizes and binds to an antibody. With diffraction you see the entire ensemble at once, in real time. You can see why I’m excited.” Douglas Rees, professor of chemistry and an investigator with the Howard Hughes Medical Institute, is collaborating on the protein work.

Caltech, being small by choice and interdisciplinary by inclination, is a good place for collaborations. Since 1996, Zewail has also been the director of the National Science Foundation’s Laboratory for Molecular Sciences at Caltech. The other members are Fred Anson (BS ’54), the Gilloon Professor of Chemistry, who is studying catalytic reactions driven by electricity; Barton; Professor of Chemistry Dennis Dougherty, who is looking at the receptor proteins in nerve cells; Rudolph Marcus, Noyes Professor of Chemistry and Nobel laureate, whose field is electron transfer (see *E&S*, Fall ’92); Professor of Theoretical Chemistry B. Vincent McKoy, who models wave-packet motion; Associate Professor of Chemical Physics Mitchio Okumura, who is examining the behavior of dissolved molecules by using small clusters of solvent molecules as a proxy for a whole beaker’s worth; and Rees. “Together,” beams Zewail, “the eight of us are doing truly exciting interdisciplinary work on very complex systems from electrocatalysis to DNA, from photoelectron spectroscopy to protein structure and dynamics—this lab is unique in the world.”

Zewail takes great pride that his entire professional life has been spent here, so the prize is truly a Caltech one. “It all started here,” he says. He takes even greater pride in being at the same institution where his hero, Linus Pauling (PhD ’25), did his own Nobel Prize-winning work on the nature of the chemical bond. (As the forces of history would have it, both men were the same age, practically to the day, when they won the prize.) Pauling worked from crystallographic data, and his bonds were static, stable, and enduring. Now, 45 years later, Zewail has set those bonds in motion, making them as alive and dynamic as chemistry itself. “I think the connection from the structure of the chemical bond to its dynamics is a wonderful legacy for Caltech to give the world.” □

