

Ultrashort phenomena

Picosecond laser pulses are the key to several new techniques for studying very rapid transient states that are being used by experimentalists in biophysics, plasmas and condensed-state physics.

Robert R. Alfano and Stanley L. Shapiro

Physicists and chemists have gained an impressive amount of new information on rapid phenomena in materials by using sophisticated new techniques for handling picosecond light pulses. The reason for the great growth of interest is not solely the development of new techniques for probing this time region, but also its importance for understanding the most fundamental processes in materials physics and chemistry. Since particle-collision rates within materials are rapid, the picosecond time scale is the appropriate gauge for a larger number of energy-transfer processes in substances.

The attack by picosecond technology on such diverse areas as photosynthesis, vision, laser fusion and exciton decays thus basically stems from the simple fact that it is necessary for obtaining first-hand information on energy-transfer processes in materials. Any other method of attack, such as measuring the frequency spectrum, yields second-hand information and often will not substitute for direct measurement in the time domain. Figure 1 shows a dual-beam carbon-dioxide laser amplifier that is used for laser fusion at Los Alamos Scientific Laboratory with picosecond diagnostics to help interpret the results of experiments.

If there is an historical analogy to the present revolutionary time domain de-

velopments in picosecond technology along with the new practical applications, we must look back fifty years to the discovery, in 1922, of the Raman effect, which led to the general method of identifying and understanding the structure of materials from spectral lines in the frequency domain.

This article briefly describes some recent rapid relaxation experiments in liquids, solids and plasmas, so that the reader can glimpse the type of work going on and get a feeling for the progress and direction in each field. It should become apparent that, although significant strides are being taken, the advancement is still in the beginning stages—indeed, in some areas the surface has hardly been scratched—and often the measurements themselves suggest new and exciting areas for further study.

The utilization of the mode-locked laser that emits light pulses of picosecond (10^{-12} sec) duration is the key to the study of rapid processes. In the techniques used to study the time development of rapid phenomena, the material is first disrupted from equilibrium by optical excitation with short intense light pulses, and then the rate of return of the nonequilibrium state to the normal state is studied by one of three basic techniques: the optical Kerr gate, a probe-beam technique and the streak camera. These techniques are described in the box on page 33. In this review article we will discuss the recent breakthroughs produced by measuring rapid phenomena with the new techniques in biophysics, plasma phys-

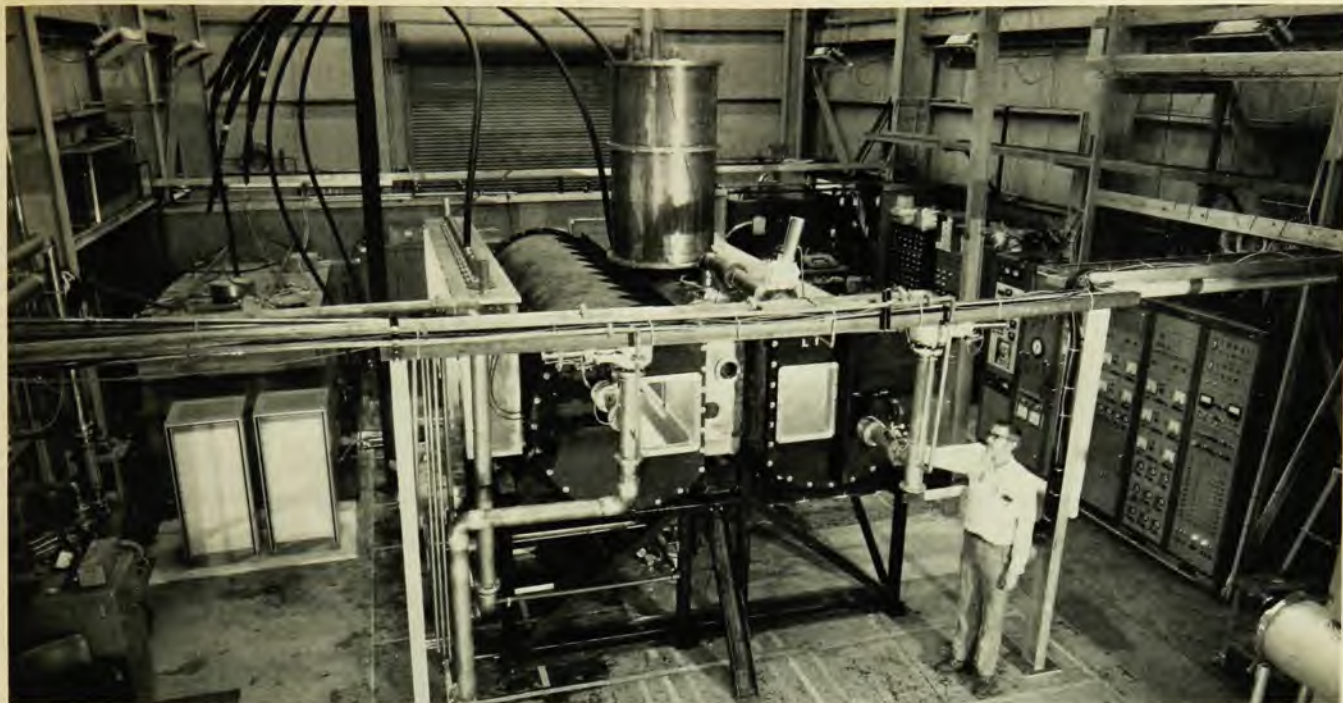
ics, solid- and liquid-state physics and chemical physics.

Biophysics

Two of the most important biophysical processes involve light—the photosynthetic processes responsible for life on Earth and, of course, the photovisual processes responsible for vision. Each process begins with light triggering the first step, and in both cases energy supplied by the light is absorbed and rapidly transferred via nonradiative processes in complicated molecules. Because of the importance of the photosynthetic and photovisual processes to us all, it is no surprise that scientists have already vigorously attacked the initial transfer and redistribution of light energy within chlorophyll and vision opsin molecules with picosecond technology, and the results appear to be exciting. We believe the primary energy-transfer steps in both processes may well be unravelled by the end of the decade.

It has long been established that the "vision" molecules undergo changes in molecular configuration as part of the visual process. Previous researchers had interpreted spectral changes observed when a vision molecule, rhodopsin, is optically excited in terms of the formation of intermediaries such as prelumirhodopsin, lumirhodopsin and metarhodopsin. Using picosecond pulses, George Busch, Meredith Applebury, Angelo Lamola and Peter Rentzepis found new evidence that the formation of prelumirhodopsin is extremely rapid. They excited rhodopsin obtained from

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In this dual-beam carbon-dioxide laser amplifier being developed for experiments on laser fusion, two laser beams will enter the front win-

dows to be amplified. Picosecond diagnostics help clarify the development of plasma interactions in the target. Figure 1

the retinas of cattle eyes with a picosecond pulse at 5300 Å and immediately upon excitation they observed an increased absorption at 5600 Å. The increased absorption was interpreted as due to the creation of prelumi-rhodopsin with a time of formation shorter than 6 picosec, the pulsewidth of excitation. Since the formation of prelumi-rhodopsin is so rapid, one conclusion must be that no major structural change takes place between rhodopsin and prelumi-rhodopsin, for there is scarcely enough time for this to happen. A transformation involving only restricted changes in the geometry of the retinyl group and its local environment is more probable. The sequence of molecular photoproducts produced in the visual process is not known with certainty and picosecond pulse technology should be readily applicable for identifying the precursor molecules.

In photosynthesis a most important process is the energy transfer in the very early stages of the primary photosynthetic process from absorbed light quanta to chemical reactions. This energy transfer is so efficient that serious proposals have been made to convert solar energy into electricity or highly transportable high-energy fuels by photosynthetic processes. A second goal is the production of huge quantities of biological materials to feed humans and animals. An enhancement of solar-conversion efficiencies may be obtainable by thoroughly understanding the fundamental processes involved. In green plants chlorophyll *a* and other accessory pigment molecules absorb light and

sensitize two different photoreaction systems, PS I and PS II. Within a photosynthetic unit, resonance mechanisms transfer the optical excitation energy from a relatively large number of pigment molecules, including chlorophyll, to a few specialized molecules at the reaction center. This initiates a sequence of electron-transfer reactions that efficiently store the light energy. The rapid transfer within photosynthetic units can be monitored by the fluorescent emission and light absorption as a function of time from the chlorophyll and accessory pigment molecules. Several processes, such as fluorescence, nonradiative energy transfer and further chemical reactions, affect the migration of excitation energy in times shorter than 10^{-9} sec. Therefore it is extremely important to probe the subnanosecond region of photosynthesis *directly* to obtain direct experimental evidence for the fundamental processes in photosynthetic kinetics.

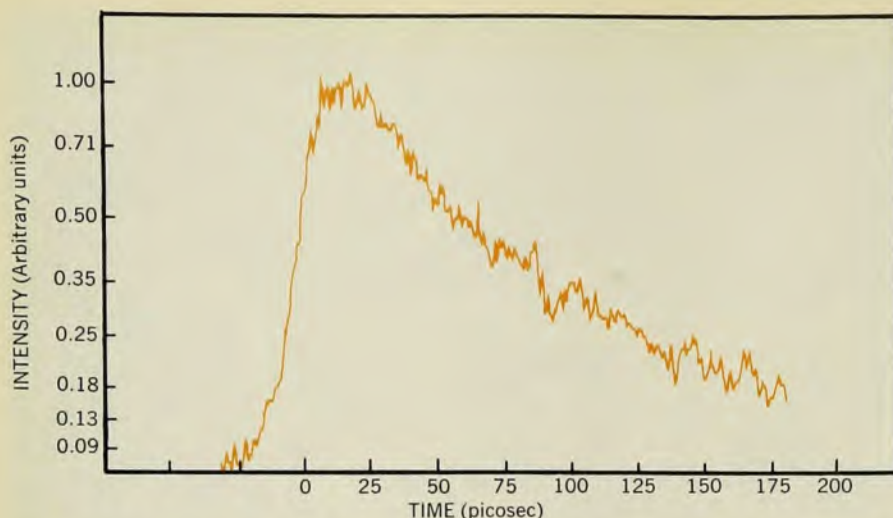
During the past fifteen years many groups have estimated the mean fluorescent lifetimes of photosynthetic units and have calculated the transfer time from antenna pigment molecules to the reaction center. However, the resolution is limited, since flash-photolysis pulse widths have been a few nanoseconds. Using the Kerr optical-gate technique with a resolution of 10 picosec, Michael Seibert, Alfano and Shapiro measured the time dependence of the fluorescent emission from chlorophyll. They found a fluorescence envelope with a 320 ± 50 psec decay time for *in vivo* chlorophyll in escarole chloro-

plasts. An interesting and surprising result is a nonexponential time-decay profile for the fluorescence. A theory attributing the nonexponential fluorescence to two independent photosystems has been recently proposed; this is in accord with a presently accepted two-photosystem model of photosynthesis. Supporting experiments on isolated PS I and PS II fractions obtained from spinach chloroplasts by William Yu, Philip Ho and Alfano yielded a fluorescent decay time of 60 psec for isolated PS I particles and 210 psec for PS II particles; the rise time was less than 10 psec for both systems. Further experiments by Anthony Campillo, Victor Kollman and Shapiro show that the nonexponential decays are observed in other systems and can be produced by nonradiative dipole-dipole transfer processes as predicted by Theodor Förster; see figure 2.

Additional picosecond work on photosynthesis has been done by Rentzepis, Tom Netzel and Jack Leigh, who used an absorption-probe technique to estimate an upper limit of 7 psec for the time to transfer energy from a particular pigment (bacteriopheophytin) to a reaction center in bacteriochlorophyll in a bacterium called *Rhodospseudomonas spheroides* strain R-26.

Plasma physics—practical applications

The most pressing problem facing technology today is the production of inexpensive energy. The controlled release of energy from nuclear reactions in a laser-produced plasma provides a possible source. How is picosecond



The decay of fluorescence from the alga *Anacystis nidulans* is nonexponential, as shown by this streak-camera photograph. An appropriate model for the first steps in photosynthesis, indicated by this result, involves the absorption of light by pigment molecules acting as antennas, followed by the migration of energy to a reaction center. Figure 2

technology used in this effort? In two ways: Picosecond pulses must be generated and amplified to obtain the energy and power levels necessary for testing the feasibility of laser fusion, and they are used to study the time-dependent interactions of the plasma with an intense light beam. These time-dependent interactions include formation of a hot plasma with a laser pulse, the compression of a small fusion pellet and the nonlinear interactions of the intense light pulse with the plasma. A detailed understanding of all the time-dependent processes is necessary for the proper design of the targets. To study these details it is necessary to probe on a shorter time scale than the pulse du-

ration, which is typically 30 to 1000 psec. Observations of the intensity of the scattered light and the spectral frequency shift as a function of time yield information on these time-dependent processes.

Recently, Barrett Ripin of the Naval Research Laboratories and his colleagues have applied picosecond diagnostic techniques to clarify some of the time-dependent processes originating in the targets. It had been noticed that a fraction of light was scattered back from the target, and stimulated Brillouin scattering (the scattering from an ion-acoustic wave) was proposed as the mechanism. It was important to clarify the nature of the interaction since light

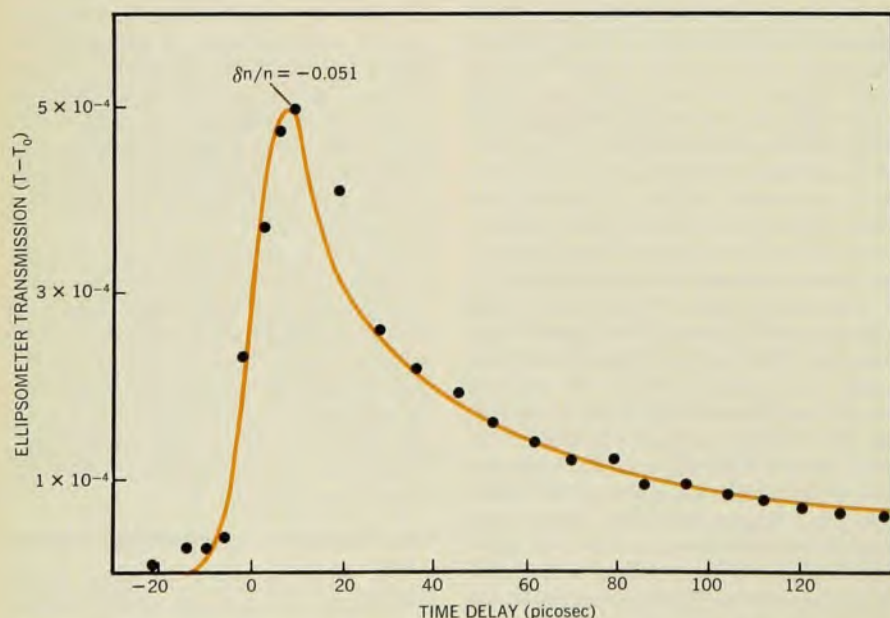
scattered backwards is energy lost and unavailable for compressing the target. Ripin's group observed the backscattered light with a streak camera and was able to show that the envelope of the backscattered light does not follow the envelope of the incident pulse but that, after a certain interval, the backscattered light builds up suddenly, in less than 20 psec. The facts that this light process has a threshold and that it grows exponentially in intensity were consistent with the equations for stimulated Brillouin scattering. The picosecond diagnostics appeared to be absolutely necessary for clarifying this phenomenon.

The time variation of the spectrum is also very interesting. Initially the light scattered from the target is shifted toward the red, indicating perhaps that stimulated Brillouin scattering is the responsible mechanism, but at later times the spectrum shifts toward the blue and is numerically consistent with a Doppler blue shift due to motion of the plasma normal to the target surface.

Another important application is by Nicholas Bloembergen and his coworkers, who have effectively measured plasma-formation times in materials. According to a model proposed by Eli Yablonovitch and Bloembergen, avalanche ionization is often responsible for the breakdown of materials when laser pulses are propagated in materials. Within a small volume of material there are always a few initial free electrons present, and these may be built up exponentially by an avalanche process in the presence of a high-power laser beam. Once the avalanche begins, dense plasmas can be generated.

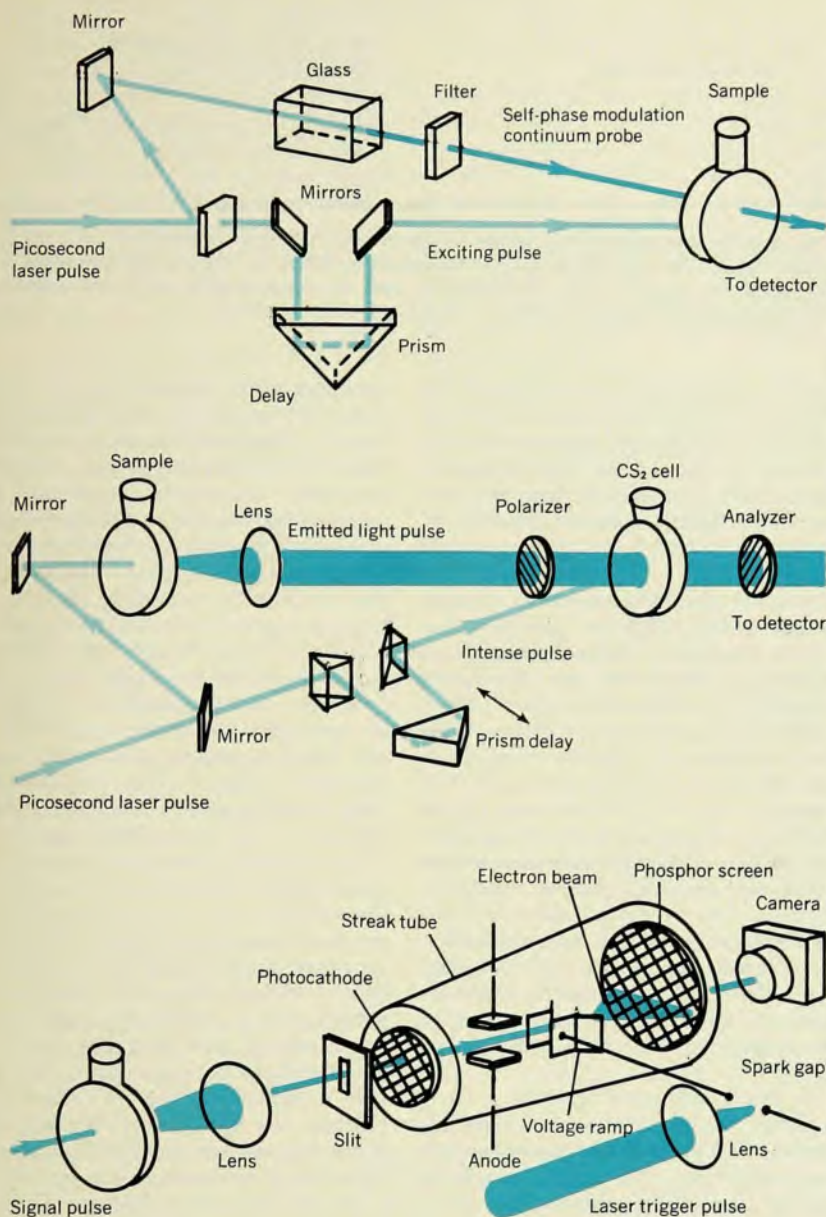
The avalanche-ionization model has been verified by measuring the field strengths at which optical damage was initiated in sodium chloride with laser-pulse durations of 15 and 300 psec. The field strength required for optical damage increases by almost one order of magnitude from 10^6 V/cm at 10^{-8} sec to more than 10^7 V/cm at 1.5×10^{-11} sec, in agreement with the electron-avalanche breakdown mechanism. Yablonovitch has also produced ultrashort pulses in gases that are breaking down rapidly.

Plasmas have also been optically generated in crystals with picosecond pulses by David Auston and Charles Shank of Bell Laboratories, who measured the time evolution of the plasmas with an ellipsometry technique. In this technique a weak pulse probes the plasma generated in germanium by an intense excitation pulse. This weak probe pulse passes through a polarizer and quarter-wavelength plates, reflects off the germanium crystal and then passes through an analyzer. When no intense excitation pulse is present, a tiny signal is detected because of the incomplete



An intense picosecond light pulse in a germanium crystal generates a plasma that diffuses into the bulk medium. The change with time of the refractive index of the material is monitored by a picosecond probe, as described in the box. (From D. H. Auston and C. V. Shank). Figure 3

Three basic techniques for measuring picosecond events



Probe technique¹

An intense pulse excites a sample. A weaker probe pulse derived from the initial pulse is reflected along a different and variable optical delay path to examine a parameter of the system such as light absorption or scattering as a function of delay time after excitation. Probe pulses can be obtained from harmonic generation, stimulated Raman scattering and self-phase modulation. The latter greatly expands the bandwidth to the so-called "picosecond continuum."

Optical-gate technique²

Light emitted from a sample can be examined with this technique. The emitted light is passed through an optical shutter composed of a carbon disulfide cell situated between a crossed polarizer and analyzer. No light is transmitted through the shutter unless an intense picosecond pulse is directed through the CS₂ cell. This intense pulse causes a short-lived birefringence due to orientation of the CS₂ molecules, and allows light from an event to be transmitted through the analyzer for a brief interval. By delaying the intense picosecond pulse through the CS₂ cell with respect to an event, different sections of the emitted light time history can be carved out for examination and an entire intensity profile of the event with time can be obtained.

Streak-camera technique^{3,4}

Light produced from an ultrafast event enters a slit and is focussed onto a photocathode where electrons are released in proportion to the light intensity. These electrons are accelerated through an anode and are then deflected by a rapidly applied voltage ramp. The increasing voltage with time in the ramp streaks the electrons across a phosphorescent screen so that electrons released at different times strike the screen at different positions. The phosphorescent track is then photographed.

1. J. W. Shelton, J. A. Armstrong, *IEEE J. Quantum Electron.* **3**, 696 (1967).
2. M. A. Duguay, J. W. Hansen, *Optics Comm.* **1**, 254 (1969).
3. D. J. Bradley, B. Liddy, W. E. Sleat, *Optics Comm.* **2**, 391 (1971).
4. M. Ya. Schelev, M. C. Richardson, A. J. Alcock, *Appl. Phys. Lett.* **18**, 354 (1971).

extinction of the two polarizers. When the intense excitation pulse generates a plasma, a large signal is measured at a silicon detector; this is due to the change of refractive index caused by generation of a plasma that leads to a phase change, inducing an elliptical-polarization state.

The transmission as a function of delay for this method is shown in figure 3. The fall time is a measure of the change of refractive index as the carriers diffuse into the bulk medium. The peak change in refractive index, -0.05 , was in excellent agreement with a simple Drude model of oscillators with a natural frequency of zero, for a free electron-hole gas. The decay time

was consistent with a linear equation for ambipolar diffusion (electrons and holes diffusing together) provided a diffusion constant about 3.5 times that expected for a low-density plasma is chosen. At the high densities of plasma generated in their experiment, about $10^{20}/\text{cm}^3$, this higher diffusion constant could be predicted on the basis of a simple model that takes the degeneracy of the plasma into account.

Solid state physics

In our opinion picosecond pulses will continue to find application in plasma physics because theoretical calculations are often insufficient for predicting the highly complex behavior of plasmas.

Many electrical, optical and thermal properties of crystals are ultimately determined by the underlying physical phenomena produced by interactions among and between electrons, holes, phonons, excitons and other fundamental excitations. Most microscopic processes involving these excitations occur on a subnanosecond scale. Included among important lifetimes measured recently are those of the phonon, exciton and polariton.

The field of exciton interactions is an area in which the introduction of picosecond technology has proven particularly revolutionary. It is now possible to create high exciton densities in a time comparable with the exciton-relax-

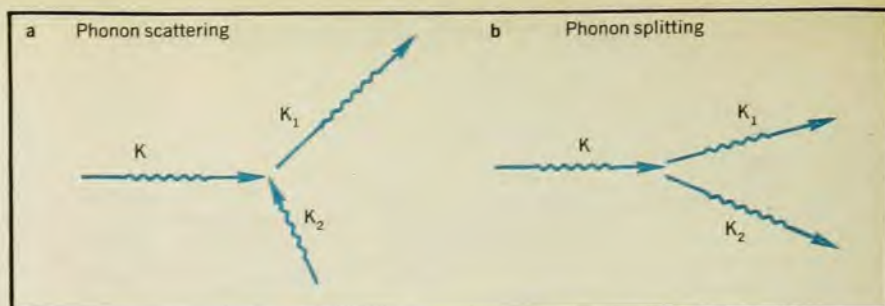
ation time. This is a key element for, as has been pointed out in the pioneering work of Herbert Mahr and his associates, many-body effects become important. At high densities, the excitons strongly interact with one another. They collide with each other, form excitonic molecules and have many unusual properties.

An excitonic molecule is formed by the covalent coupling (like that of a hydrogen molecule) of two excitons. Mahr's group has discovered new emission bands attributable to the formation of excitonic molecules, to exciton collisions and to collisions of molecular excitons. Both they and Shigeo Shionoya and his coworkers have used a picosecond optical Kerr gate to study the time dependence of the luminescence from excitons. Their work has provided formation and decay times of the free exciton and the excitonic molecule, and collision times between two free excitons and between two excitonic molecules.

Perhaps the most striking use of picosecond pulses is the possible observation of Bose condensation of excitons. Excitons can be regarded as bosons since they are composed of an electron and hole bound together. It has been predicted that if excitons are produced rapidly at high enough concentrations, about $10^{17}/\text{cm}^3$, they may condense to a state of zero momentum at a suitably low temperature.

The luminescence spectrum of cadmium selenide at 1.8 K and 4.2 K exhibits an extremely sharp luminescence line under picosecond laser excitation on the lower-energy side of the spectral profile. This line was produced within a limited excitation range and the line shape was consistent with a theoretical Bose condensation model. Sharp lines can also be produced by impurities and stimulated emission processes—but the most intriguing interpretation is Bose condensation, in which the picosecond pulses would rapidly generate the required high density of excitons without heating the lattice.

Another example in which the optical phonon plays an important role is the exchange of energy in many solid-state processes. In a pure crystal, due to the anharmonic nature of the potential-energy curves of the lattice, phonons decay by scattering with other phonons in a crystal or by breaking up into multiple phonons, as depicted schematically in figure 4. The dominant decay mechanism for phonons at high temperature is collision with thermal phonons, while at low temperature a phonon spontaneously decays into two or more phonons. Using picosecond-pulse probe techniques, we found the lifetime of the 1086-cm^{-1} optical phonon of calcite to be 8.5 psec at room temperature and 19 psec at 100 K while Wolfgang



Phonon-decay processes due to lattice anharmonicity. At room temperature, phonons decay by colliding with the many other phonons present in the lattice (a), while at low temperatures the phonons decay spontaneously by splitting (b), with the coupling provided by the anharmonic crystal. Optical phonons have greater lifetimes at low temperatures. Figure 4

Kaiser and his coworkers estimated the lifetime of optical phonons in diamond to be 2.9 psec at room temperature and 3.4 psec at 77 K. The lifetime lengthens at lower temperature because there are fewer thermal phonons present in the lattice to collide with the generated phonons.

Another recent experiment demonstrates interactions of particles not among themselves but rather with an impurity. Impurities are sometimes important in solid-state devices, often hindering their operation but in some cases playing an essential role. Dietrich von der Linde and Auston of Bell Labs have studied the dynamics of an optical rectification device with picosecond pulses. Optical rectification occurs when an optically excited impurity atom in a crystal decays nonradiatively and emits phonons that heat the lattice, thereby causing pyroelectric polarization in some crystals. The nonradiative decay is rapid and plays a key role in the development of the induced polarization.

To study this rapid transfer, a Cu^{2+} impurity ion in a lithium tantalate lattice was first excited with an intense picosecond pulse. The energy transfer to the lattice was then obtained by monitoring the decay of the populated state by measuring the absorption from the excited state to a higher charge-transfer state of a second probe pulse at 0.53 microns. The absorption decayed exponentially as a function of the delay between the excitation and the probe pulses. The lifetime ranged from 450 psec at 22 K to 10 psec at 423 K, which demonstrates the role played by phonons in this device.

Recently Auston has developed a silicon opto-electronic switch in which picosecond light pulses generate and manipulate electrical signals with picosecond precision. His invention opens up the possibility of a new high-speed electronic technology.

Liquids

Picosecond-probe techniques have also provided a great deal of insight on

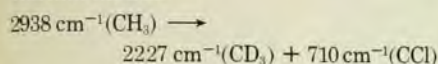
how molecules interact in the liquid state. Molecular vibrations in a liquid have a depopulation time associated with transferring the energy internally to other vibrational, rotational and translational modes within the molecule or to other molecules. A second relaxation time, called a "dephasing time," is the duration for molecules that are vibrating together coherently to go out of phase relative to one another.

The equations governing the decay of both the population and the amplitude of molecular vibrations are similar to the Bloch equations that govern magnetization decay. The depopulation time is analogous to T_1 and the dephasing time to T_2 in the Bloch equations. Experimentally these two times can be conveniently separated. To measure the depopulation time of a vibration the probe is beamed on the vibration at an arbitrary angle of incidence and the light scattered from the vibrations is detected at an arbitrary angle. The amplitude of the scattered light depends only on the population. To measure a dephasing time for coherent vibrations one must observe the scattered probe beam at an angle such that conservation of momentum is preserved between the momentum vectors of the involved photons and the coherent molecular vibration. Albert Laubereau, von der Linde and Kaiser measured the decay of polyatomic molecules in the liquid phase. For ethanol they found that the depopulation time was 20 psec, with the dephasing time about 80 times shorter.

When the vibrations depopulate, new vibrations are formed. By examining the spectrum of the probe Raman light scattered from the vibrations, the dynamics of the formation and decay of these new daughter vibrations can be determined. Our first vibrational decay route measurement demonstrated that the methyl (CH_3) vibration at 2928 cm^{-1} in ethanol ($\text{CH}_3\text{CH}_2\text{OH}$) decays into daughter vibrations at 1464 cm^{-1} , where there are two vibrational modes. From the amplitude of the spontaneous scattering off these newly

created vibrations we determined that this must be the main decay route in ethanol for the 2928-cm⁻¹ vibration.

Another interesting measurement, by Laubereau, L. Kirschner and Kaiser showed that in a liquid mixture of trichloroethane (CH₃CCl₃) and deuterated methanol (CD₃OD), the 2938-cm⁻¹ vibration of trichloroethane can de-excite by transferring its energy to the 2227-cm⁻¹ methyl vibration in deuterated methanol. This mixture was chosen because of the possible three-quantum resonance energy transfer between the normal modes:



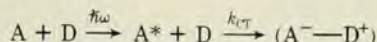
The measured intensity of the daughter vibration is high, indicating that efficient transfer has occurred. Furthermore, by measuring the decay times as a function of concentration, two- and three-body collisional mechanisms were established for the exchange of vibrational energy by Laubereau and his associates and by Alfano.

Chemical physics

Picosecond pulses have already found numerous applications in chemical physics. They have been used to observe ultrafast chemical reactions, new short-lived transient states, "cage effects," rapid nonradiative decay processes, and vibrational and rotational decay constants of molecules in liquids. We will mention only a few of the more recent results.

Recently Tung Chuang and Kenneth Eisenthal of the IBM Research Laboratory (San Jose) have for the first time directly measured the rate of formation of a charge-transfer complex. These complexes arise from the transfer of an

electron from a donor molecule to an excited-state receptor molecule to form a stable complex, as represented schematically by



where k_{CT} is the rate constant for charge transfer. In Chuang and Eisenthal's studies the complex was formed by mixing anthracene (the acceptor molecule A) and N,N'-diethylaniline (the donor molecule D) in n-hexane solvent and exciting anthracene with a picosecond pulse at 3472 Å. Upon formation of the charge complex a new absorption is detected at 6943 Å because of the transition



Since the absorption coefficient at 6943 Å is a measure of the number of charge-transfer complexes formed, the dynamics of charge-transfer complex formation may be obtained by monitoring the new absorption as a function of the delay time from excitation. Chuang and Eisenthal found that at the earliest and intermediate times transient terms such as those in the Smoluchowski diffusion model or the Noyes molecular-pair model are evident in their data. At longer times (≥ 300 psec), their results show that k_{CT} is close to the steady-state diffusion rate constant. Thus for the first time they were able to observe the complete transient behavior predicted by models of reaction kinetics.

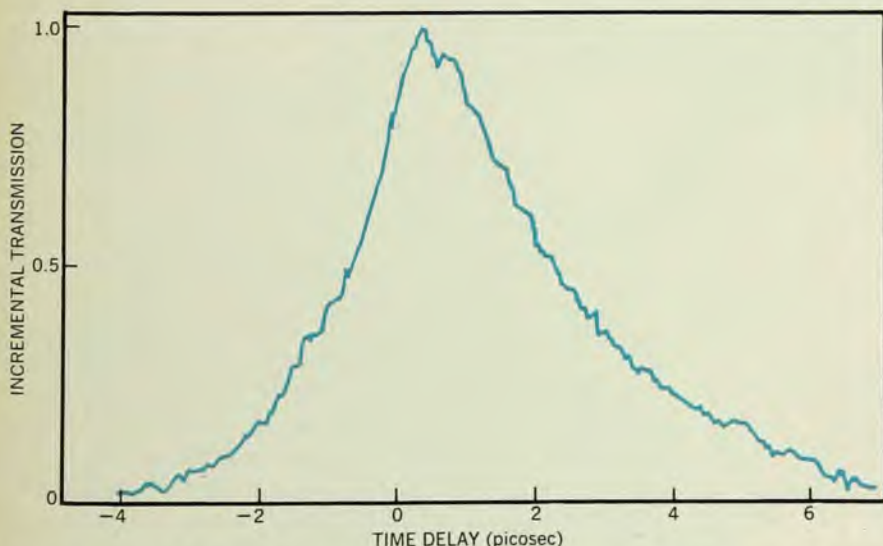
Chuang and Eisenthal along with Geoffrey Hoffman have also made picosecond studies of a "cage effect" in liquids. Iodine atoms in a solvent are generated by dissociating I₂ by photoexcitation with an intense picosecond

pulse at 5300 Å. In the liquid phase, unlike the gas phase, these iodine fragments have a high probability of recombining with their original partners, because the surrounding solvent molecules effectively form a cage and interfere with the escape of the iodine fragments. The number of iodine molecules present at any given time after excitation was monitored by measuring the absorbance of a weaker 5300-Å pulse, which was split off from the main pulse and variably delayed with respect to the photodissociating strong pulse.

The results show that the transmission of the probe pulse through a 10⁻²-molar solution rises quickly, demonstrating immediate dissociation, and then decays in 140 psec, showing geminate recombination (recombination with original partners) of the iodine atoms. A residual transmission that becomes evident 800 psec later shows that some iodine atoms have escaped their original partners and slowly recombine via diffusion-controlled reactions with other iodine atoms. The data are in reasonable agreement with a theoretical model due to Noyes, which is based on the probability of encounter of fragments in a random walk. From these types of experiments useful information is obtained—not only on reaction kinetics of the species in liquids, but on the liquid state as well.

Impressive experiments have been recently carried out by Robin Hochstrasser's group on energy transfer between singlet and triplet states of dye molecules in various liquids. Measurements of the buildup and decay time of triplet-triplet absorption at 5300 Å of dyes have been made during and subsequent to the excitation of a singlet state of a dye by a 5-psec pulse at 3545 Å. One of the most interesting experiments of the series is for benzophenone dye dissolved in perylene solvent. In this case there is a good overlap between the triplet states of benzophenone and perylene. Energy transfer between the triplet states of both dye and solvent can readily occur. Hochstrasser and other members of his group found that triplet-triplet absorption of benzophenone builds up in 7 psec and then rapidly decays in 9 psec. This rise and decay indicates a very rapid singlet-triplet internal conversion in benzophenone dye and a rapid intermolecular triplet-triplet energy transfer between the dye and solvent.

Orientational relaxation times for molecules in liquids were first measured directly by Michel Duguay and John Hansen, and by Eisenthal and Karl Drexhage using picosecond techniques. Recently Shank and Eric Ippen of Bell Laboratories have used subpicosecond pulses (0.7 psec) generated by passive mode-locking of a CW dye laser together with an optical Kerr shutter to mea-



The orientational relaxation time of carbon disulfide molecules in the liquid phase is shown by this graph (after deconvolution) to be just 2.1 picoseconds. This result indicates that ultrashort lifetimes may be measured accurately with the optical-gate technique using CW mode-locked lasers, described in the box on page 33. (From E. P. Ippen and C. V. Shank.) Figure 5



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sure an orientational relaxation time (after deconvolution) of 2.1 psec in carbon disulfide, as shown in figure 5. This result demonstrates the capability of the subpicosecond laser for accurately measuring events of extremely short duration. The availability of a continuous source of subpicosecond pulses facilitates certain short-pulse experiments by allowing the use of averaging techniques required at low signal levels.

A streak camera with a resolution in the 10-psec range has been used to measure the time evolution of fluorescence from dye-vapor molecules by Shapiro, Campillo and Ronald Hyer of Los Alamos Scientific Laboratory. A pulse at 0.353 microns pumps samples of perylene and dimethylpop molecules to an excited state, and the fluorescence generated by the pulse is projected into the streak camera. The fluorescence rises instantaneously (in less than 20 psec) indicating a rapid deactivation of the excited state of the molecule. This measurement is important because it shows that large molecules can relax in the absence of collisions. Their rapid deactivation is possible because they are so large (50 atoms) that their numerous vibrational modes allow them to relax internally by multi-vibrational processes.

Daniel Bradley, a coinventor of the streak camera, has now reported the development of a streak camera with a demonstrated time resolution of 0.5 psec. This very high resolution should be very important for uncovering phenomena in the subpicosecond domain.

Finally, we mention a new development due to Duguay and coworkers who have invented an ingenious picosecond sampling oscilloscope and have already used this device to measure picosecond x-ray pulses. The components of their device are very inexpensive and should be useful to many experimenters in the field.

We look forward to an increased use of laser technology with picosecond and subpicosecond times by experimenters whose interests have led them to study the fundamental processes of nature.

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