Robin M. Hochstrasser

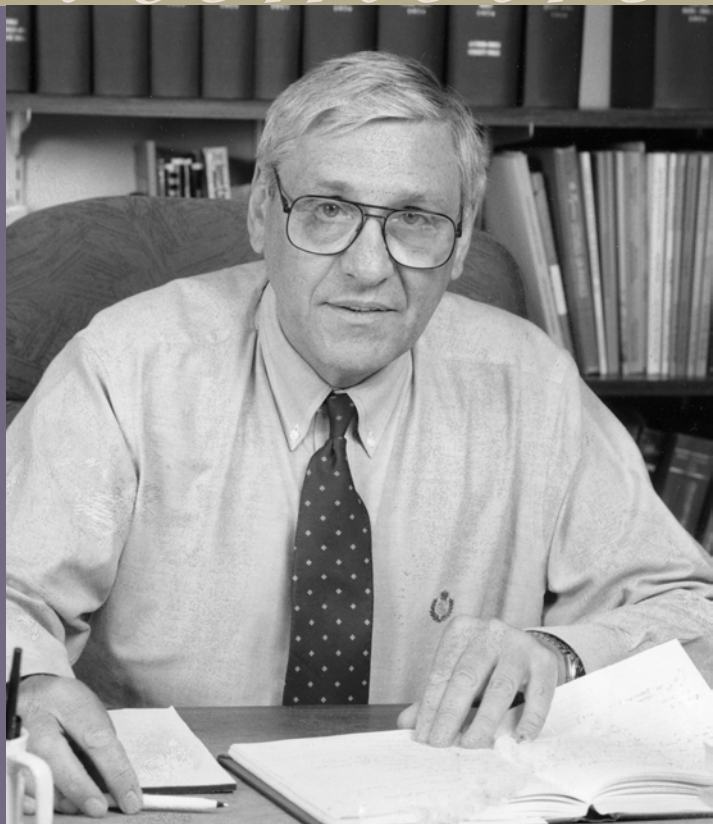## 1931–2013

BIOGRAPHICAL *Memoirs*

*A Biographical Memoir by
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Graham R. Fleming,
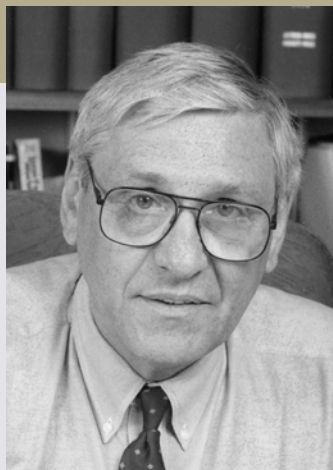and H. Peter Trommsdorff*

NATIONAL ACADEMY OF SCIENCES

ROBIN MAIN **HOCHSTRASSER**

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Elected to the NAS, 1982

Robin Hochstrasser was one of the truly great physical chemists of the past 50 years—a pioneer in molecular spectroscopy and in the application of lasers in chemistry. Using advanced laser-based techniques to address questions of molecular structure and dynamics, Hochstrasser impacted all branches of chemistry. His trademark was creativity, as he repeatedly managed to carry out totally new kinds of experiments thought by his peers to be impossible at the time. The result was a constant stream of groundbreaking experiments and novel ideas from the early 1960s until his death in 2013.

A native of Edinburgh, Scotland, Hochstrasser earned a B.Sc. degree from Edinburgh's Heriot-Watt University in 1952 and a Ph.D. in chemistry from the University of Edinburgh in 1955. After serving two years in the Royal Air Force, he became an instructor and, later, an assistant professor at the University of British Columbia. In 1963 he moved to the University of Pennsylvania, where he advanced to full professorship and over time held two different endowed chairs. He spent the rest of his career at Penn.

By William A. Eaton,[1]
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Robin Main Hochstrasser was born and educated in Edinburgh, Scotland. His education as a teenager was unconventional, as he left school at 15 when his family planned to relocate to Belgium but returned after several months. Without ever returning to regular school in 1948 at age 17, he passed the college entrance exams (with perfect scores in mathematics and chemistry). He received his B.Sc. degree from Heriot-Watt University, in Edinburgh, in 1952 and his Ph.D. in chemistry from the University of Edinburgh in 1955. He wrote his dissertation on the topic of surface photochemistry (4). Conscripted for two years into the Royal Air Force as a pilot officer, he taught the basic

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electronics associated with high-altitude radar displays. During his two years in the R. A. F. Robin took a correspondence degree in mathematics, which helped him to become very proficient at applied mathematics and to write a rigorous textbook on group theory (5). He joined the faculty of the University of British Columbia (UBC) in 1957 as an instructor and became an assistant professor in 1960. That same year he married Carol Ostby, from Vancouver, whom he met at the university. He moved to the University of Pennsylvania in 1963, where from 1968 he was the Blanchard Professor and, after 1983, the Donner Professor of Physical Sciences. Robin

Robin and Carol, 1960.

was very much attached to both the university and Philadelphia and, in spite of many attractive offers, stayed at Penn for the remainder of his career.

Early career

Robin described his time in the Chemistry Department of UBC thus (1):

> At UBC I began studying gas-surface reactions to seek quantitative descriptions of the mechanisms of reactions of oxygen with thin films of aromatics, but I soon became much more interested in the spectroscopy, theory, and photophysics of molecules…I became convinced that molecular spectroscopy was the most exciting direction for me to pursue. My impression was that new computational methods were making predictions that needed to be verified and challenged by experiment, and the possibilities for designing experiments to explore light induced processes seemed unlimited. At the Ohio State Symposium on Molecular Structure and Spectroscopy Meeting in 1959, my first trip to the United States and my first opportunity to meet the scientists whose papers I had been reading, I recall energized discussions with John Platt, Klaus Rudenberg from Iowa State, and others from the Chicago theory group. Mike Kasha

Robin in lab, circa 1970.

chaired the session in which I talked, and I enjoyed meeting Don McClure, Mostafa El Sayed, Herb Broida, Norman Sheppard, Otto Schnepp, and G. Wilse Robinson, all experimentalists who worked with molecules in the condensed phase.

On leave from UBC for the 1961-'62 year, Robin went to the National Research Council in Ottawa, hosted by William G. Schneider, and subsequently to the Florida State University in Tallahassee. In Ottawa, helped and encouraged by Alec Douglas in Gerhard Herzberg's laboratory, he discovered how broad spectra of molecular crystals transformed into highly resolved spectra at liquid-helium temperatures that could be analyzed in detail. In Tallahassee, he was invited by Michael Kasha:

Mike was an inspirational colleague, and in that environment the seeds of many of my subsequent research ideas became more firmly planted. Mike had just launched the Institute of Molecular Biophysics for which a building was being built when I was there. I had fruitful discussions on group theory with the young faculty member Bill (W. C.) Rhodes who was working on the optical spectrum of DNA. Many visitors, including Theodor Forster, Robert Mulliken, Bernard and Alberte Pullman, William T. Simpson, and others, overlapped with my stay, so this was an extremely stimulating environment (1).

When Robin moved to the University of Pennsylvania, with a Sloan Fellowship, he set up his labs in the new Laboratory for Research on the Structure of Matter. The spectroscopy of polyatomic molecules was a blossoming field of research in the 1960s; it promised the possibility of being able to characterize the electronic structure and nuclear force fields that determine these molecules' geometry and properties and of relating these measurements with the predictions of rapidly progressing quantum chemical calculations. Robin's initial work focused on the study of molecular crystals, where intra-molecular interactions and forces exceed by more than an order of magnitude intermolecular interactions. He realized that the oriented-gas model, which neglects all intermolecular interactions, is, therefore, a good zeroth-order approximation of a molecular crystal. Regarding the lowest energy states

of aromatic molecules, heterocyclics, and other conjugated molecules, the complexity of spectra is greatly reduced and the analysis is simplified by recording the spectra of oriented single crystals with polarized light at low temperatures. For crystals with unknown structure, these spectra contain structural information—an important aspect at a time when the determination of a crystal structure of an organic molecule was a whole thesis project (6).

Going beyond the oriented-gas model, Robin became interested in intermolecular inter-actions, of prime importance for the description of materials and for molecular engineering, which has led to the development of passive and active molecular materials used in numerous everyday applications. In pure crystals, excitation-exchange interactions give rise to collective excitations (excitons) with a wave-vector-dependent energy dispersion and splittings of the optically observable k=0 states.

With the work of the Russian school in Kiev, the exciton splitting of singlet states was fairly well understood as arising primarily from dipolar coupling, but for triplet states both measurements and theoretical understanding of exciton splitting were absent. Transitions between a singlet ground state and triplet excited states are spin forbidden and are observed only with very low intensities due to small spin-orbit coupling terms, which admix a weak singlet component to the triplet state.

In a tour de force, Robin set up optical experiments in the National Magnet Laboratory at the Massachusetts Institute of Technology and observed in 1965 the first Zeeman splittings in the spectra of molecular crystals (7). He then extended these measurements to many other molecules. The process required the growth of single crystals of several centimeter thicknesses, strain-free cooling to liquid helium temperatures, and the transporting of the entire optical set-up to the magnet laboratory. By this means he could determine the spin-orbital coupling and the symmetry of the perturbing singlet state and open up new perspectives for the study of triplet states.

Robin extended these studies to a variety of prototype aromatic molecular crystals and combined them with applied electric fields. A thorough theoretical analysis of these experiments leads to the complete unraveling of the exciton-spin substructure and to a determination of the relevant zero-field splitting and excitation-exchange parameters. A beautiful example is Robin's work on the benzophenone crystal with four molecules in the unit cell, where the 12 k = 0 sublevels, all located within the inhomogeneous line-width of less than one wavenumber at zero field, could be separated and assigned (8).

The prototype aromatic crystals of benzene, naphthalene, and anthracene were of particular interest as test cases for theoretical evaluations of the triplet exchange interactions. Confrontations with experiment were crucial: for naphthalene the magnitude and ordering of the exciton levels agreed, but for anthracene the ordering of the levels was reversed (9, 10, 11). Benzene, with four molecules in the unit cell, was therefore an important test case, and different predictions for these parameters had been made. Robin analyzed this crystal based on approximate symmetry arguments that had successfully been applied to the singlet exciton levels (12). In 1975 he told one of the authors (H.P.T.) that he had done the calculations during a long flight to Australia using the new programmable HP-65 pocket calculator, and suggested that H.P.T. do the measurements, a task that had just became technically feasible. As it turned out (13), all different predictions were in disagreement with experiment, and this put a term to these confrontations as it was realized that the accuracy of quantum chemical calculations of the tails of the electronic wave functions in the regions of overlap between different molecules was just not sufficient at that time.

In 1967, two years after the first successful magnetic field measurements, Robin pioneered electric field studies in molecular crystals. He showed that excited state dipole moments could be obtained with relative ease, while prior to this work the values were known for only four small molecules, from vapor-phase studies. Now such determinations could be made for many different transitions of the same molecule in the same environment, where local fields were near identical, and produced valuable information about the charge distribution in excited states, related, for example, to photochemical properties. Robin could obtain differences between singlet and triplet states and observe changes as a function of vibrational excitation in regions where different electronic states interfere.

Quite naturally such studies were subsequently initiated in many different groups, and Stark spectroscopy—based on the Stark effect, which is the shifting and splitting of spectral lines of atoms and molecules in the presence of an electric field—in molecular solids became a booming field of research for many years. By 1972, from Robin's laboratory alone, data on dipole moments were published for tens of molecules in different excited electronic states and in different host matrices (14), and new states of molecules were discovered through the electric field mixing of gerade and ungerade (even and uneven) states (15).

Combined electric and magnetic field studies were also helpful in elucidating the Jahn-Teller effect in degenerate states of molecules of high symmetry, where molecular deformations of appropriate symmetry can lift the degeneracy, a topic of great interest at that time. Benzene with a six-fold and s-triazine with a three-fold symmetry axis were much-studied prototype examples, giving rise to lively controversies in the literature as well as at conferences. In Robin's own recollections (1):

> *Involved in these illuminating controversies about s-triazine's putative degenerate states were a number of individuals who went on to make significant impacts on other areas of chemistry, including Tom Lin and Ahmed Zewail, who were my students; Rick Smalley, who was a student of Elliot Bernstein at Princeton; Douwe Wiersma, who had recently returned to the Netherlands after being a postdoctoral fellow in my group; and my ex-student Gerry (G. J.) Small, who was based in Canberra with David Craig's group. I recall that Elliot and I joined our two students, Rick and Ahmed, at the Philadelphia American Chemical Society meeting in 1972 to discuss differences that had arisen in their work on s-triazine: Later they would both win Nobel Prizes—but in quite different fields.*

The dimensionality of interactions and the topology of energy transport play an important role in light-harvesting and photosynthetic processes as well as in material science. Molecular crystals with well-defined packing have the perspective to engineer and thus to control these interactions and to provide model systems for experimental studies and test cases for theoretical descriptions. Robin searched for lower-dimensional systems where excitons are confined to one or two dimensions, and he demonstrated that the triplet exciton in 1,4-dibromonaphthalene crystals was essentially one dimensional, being confined to linear chains of molecules (16). The interactions in perpendicular directions were shown to be negligible.

Since the exciton coupling of triplet states is confined to nearest neighbors, isotopic substitution, which introduces energy disorder without disturbing the crystalline order, provided a means of isolating shorter fragments of these chains. Excitons, confined to well-defined clusters of up to four molecules, were spectrally isolated and characterized in detail. Following Robin's work, 1,4-dibromonaphthalene became a favorite model system studied by numerous research groups. Much later, σ-conjugated polysilanes provided a very different one-dimensional system, one where geometrical defects limit the electronic delocalization. The exciton dynamics of these photo-conducting polymers was elucidated

via ps time-resolved and high-resolution hole-burning studies (17). Subsequently, Robin characterized with femtosecond time resolution the exciton dynamics in biological and synthetic light-harvesting systems (18).

From very early on, Robin was interested in the origin of the line shapes observed in molecular spectra in condensed phases (19). He addressed issues of the coupling between excited states of a molecule, observed as spectral perturbations (20), as well as the coupling with the environment (21). The underlying issues concerned the relation of line shapes with dynamics: how excitation energy is redistributed and dissipated, leading to local heating. Subsequently, the advent of pulsed lasers enabled addressing these issues with line-narrowing techniques and direct-time-resolved measurements.

The arrival of lasers

The 1960s witnessed the introduction of lasers, which revolutionized optical spectroscopy. The invention of powerful pulsed lasers and the rapid development of techniques enabling measurements on pico- and femto-second time scales took place in many laboratories and were highly exciting as well as highly competitive. From the beginning, Robin was a major player in this game, operating continuously at the cutting edge of evolving technologies.

In 1969 he obtained the first Nd-glass laser with a repetition rate of about one shot per minute, intending to make direct-time-resolved measurements. But years of hard work by his students and post-doctoral fellows were needed before such measurements could reliably be made. The early time-resolved measurements used different harmonics of an amplified Nd-glass laser as excitation and probe pulses, and time-sliced spectra were recorded photographically using a continuum generated by the pump laser pulse for absorption or an optical Kerr cell as shutter for emission; but 95 percent of the researchers' time was spent aligning and monitoring the laser. Robin pushed very hard for obtaining reliable data that were meaningful and relevant to issues related to his scientific interests. Results for intersystem crossing kinetics and energy transfer between triplet states were obtained for a variety of molecules, and the first publications were submitted in the early '70s (22, 23, 24). While artifacts often spoiled published data, it is remarkable that Robin's work has by and large survived the test of time.

A little later the invention of easily constructed, widely tunable, narrow-band lasers (25) opened new avenues. Robin's lab immediately built one of these lasers and, shortly thereafter, recorded the first high-resolution two-photon spectra of a biphenyl crystal

(26), followed by spectra of benzene in the crystal and in vapor phase (27). The first rotationally resolved two-photon spectrum was observed using nitric oxide at low pressures (28). These experiments, unexpected by many specialists in the research community, stirred immense interest and stimulated related studies in numerous other groups around the world. Robin's lab very quickly converted entirely to lasers: old spectrometers were cannibalized to construct new dye lasers, and all research was impacted.

Tunable lasers opened the possibility of selectively exciting molecules in an ensemble, as well as addressing specific energy levels within a molecule and initiating and studying state selective processes. This was the dream of many photochemists. Robin, with his colleague Amos Smith, used tetrazine and derivatives in crystalline benzene and rare gas matrices to demonstrate isotope selective photo decomposition and to achieve isotope enrichment factors exceeding 10^4 (29), in addition to elucidating the reaction pathway and demonstrating the spin selectivity of the reaction. Later, the dissociation of a derivative of this molecule was used as a trigger of structural changes in biomolecules (30).

The possibility of confronting time and frequency domain experiments in laser spectroscopic studies stimulated Robin to seek a deeper understanding of light-matter interaction and the relations between line shapes and dynamics in condensed phases. He addressed the issue of how to distinguish and to describe properly the time dependence and spectral line shapes of resonance Raman scattering and fluorescence (31, 32). In a series of experiments on the resonant emission of single vibronic levels of azulene in naphthalene, he demonstrated how the sharp Raman scattering shifted with the laser frequency, while the fluorescence was induced by fluctuations and exhibited the full dephasing width of the electronic transition. Fifteen years later, the influence of dephasing processes was beautifully demonstrated in coherent anti-Stokes Raman scattering experiments and described as dephasing-induced coherent emission (DICE): vibrational spectra of unpopulated excited states of pentacene in a benzoic acid host crystal were induced as the temperature increased (33). This effect was analogous to the pressure-induced extra resonances in 4-wave (PIER-4) mixing experiments performed around the same time by Niko Bloembergen and his collaborators (34).

Coherent nonlinear and ultrafast processes

With pulsed lasers, nonlinear material responses, such as frequency doubling and frequency mixing, became easily observable. The use of different tunable incident beams opened up the field of coherent nonlinear spectroscopy by enabling monitoring of the enhancement of the generated beams when the combination of incident frequencies

matched a material resonance. The possibility of adjusting not only frequencies and polarization but also the directions and time delays of the incident beams led to myriad new experiments around the world, described by a large number of acronyms, such as DICE and PIER-4.

Robin was interested in accessing information about excited-state properties and relaxation processes and became a leading figure in this field of resonant molecular optics (35, 36). In collaboration with Penn colleague David White, he characterized the coherence decay of vibrational and librational excitations in the simple diatomic crystals of N_2 and H_2 and developed theoretical concepts that became important in understanding these processes in larger molecules in crystals and in solution (37). At that time, little was known about vibrational relaxation times in larger molecules, and the discovery that these could be very long in crystals of aromatic molecules was exciting and unexpected (38). Robin went on to show the high-mode selectivity of these relaxation processes in pure and isotopically mixed crystals—information that was the basis for theoretical modeling and understanding (39). The coherence-decay times were obtained through both line-shape analysis and direct temporal measurements. A particularly startling result was the discovery that the coherence-decay time of the 606 cm^{-1} mode of crystalline benzene increases from 95 ps to 2.65 ns in crystals made of the pure carbon-12 isotopologue (40). This finding demonstrated dramatically the importance of impurity and defect scattering through the presence of isotopic impurities in natural abundance (^{13}C).

During the 1980s Robin explored many other avenues for using coherent nonlinear optical processes and developed the corresponding theoretical tools for accessing information about excited-state properties and relaxation processes: energy-transfer and -relaxation processes of electronic, vibrational, and rotational states and energy dissipation, as well as chemical reactions. Many of the processes of interest take place in dilute liquid solutions at ambient temperature, where phase relaxation is very rapid, so that conventional electronic spectra become broad and selectivity is lost. For vibrational transitions the spectra are better resolved by more than an order of magnitude, so to achieve a higher selectivity, Robin pushed ultrafast laser methods to vibrational transitions in the IR spectral region. He conceived and developed a particularly ingenious idea of combining ultrashort visible laser pulses to excite a molecule with a spectrally highly resolved infrared beam from a continuous diode laser to record vibrational fingerprints of transient species. He achieved the time resolution by up-converting the IR, assuring an uncertainty-principle limited-time and -spectral resolution, where the time scale is imposed by the dynamics of the system studied and not by the laser instrumentation

(41). These methods made it possible for him to record in heme groups the iron-carbonyl-bond geometry during dissociation reactions with unprecedented sensitivity and precision (42).

Ten years later Robin invented and developed 2D IR spectroscopy, a powerful technique in particular for biophysical problems, as discussed below. These advancements, particularly important for the study of biomolecules, were made possible by the progress of laser technology, enabling the control of the light fields and conceiving optical analogs of nuclear magnetic resonance (NMR) spectroscopy.

Reaction dynamics and the isomerization of stilbene

Robin was interested in the dynamics of chemical reactions and studied a number of prototype molecular systems where reactions could be photo induced. Factors that govern the dynamics are the height and shape of the barrier-separation adduct and product, excitation energy, temperature, and the frictional forces of the environment. The issue of whether or not processes such as isomerization could occur in large molecules under collision-free conditions was actively debated at the time, when Robin showed that the trans- to cis-isomerization of stilbene about the central double bond occurred under collision-free conditions with a rate that was excitation-energy dependent (43, 44). For excess energies of 1 and 0.65 eV, the excited-state decay times increased from 15 to 55 ps. Subsequently he persuaded his former student, Ahmed Zewail, who had just completed the construction of a beam apparatus, to make the first determination of a state-selective isomerization by recording both fluorescence lifetimes and intensities of individual vibrational levels with excess energies ranging from 0 to 0.18 eV (45). These results clarified the energy dependence of the isomerization reaction and provided a determination of the barrier height.

Robin's main interests, however, were in reactions in solution and a comparison with isolated molecule behavior. He investigated a number of different systems, but the cis↔trans isomerization of stilbene remained his workhorse: over a period of 16 years he published more than 25 papers on this topic. The Kramers theory of reaction rates for thermally activated barrier-crossing processes provided a theoretical basis for the description of these processes. According to Kramers theory, the reaction rate varies non-monotonically as a function of viscosity and goes through a maximum for some value of friction, which marks the transition from collisional to diffusive kinetics and at which point the transition state rate can be obtained. The search for this so-called

Kramers turnover was a holy grail of reaction theory and had been the object of numerous studies.

Robin studied the isomerization dynamics of stilbene and "stiff stilbene" (a derivative of stilbene in which the rotation of the phenyl groups around the single bond is inhibited) as a function of viscosity in the series of C_4 to C_{16} n-alkanes, but he could observe no maximum of the rate (46). In order to go to still lower viscosities, he chose supercritical liquid ethane as solvent, varying the viscosity by changing the applied pressure up to 170 atm. Under these conditions, a turnover of the isomerism rate could be demonstrated at pressures of about 125 atm at 350 K (47). This beautiful experiment marked one of the first verifications of the turnover predicted by Kramers.

Robin continued to work on the topic of reaction- and solvent-dynamics and addressed issues such as the dimensionality of the reaction by comparing stilbene and stiff stilbene; the formation of reaction intermediates; the competition between different relaxation processes of internal redistribution of vibrational energy leading to the establishment of an internal temperature and the cooling of the hot molecule; and the dynamics of overall rotation and rotation about the double bond as well as the solvent dependence of all these processes. His pioneering work provided much of the knowledge required for understanding and modeling excited-state and reaction dynamics in condensed phases.

Many more topics that Robin made contributions to can only be enumerated here: surface studies; conducting polymers; ultrafast charge transfer; proton dynamics in H-bonds; vibrational relaxation of ions in aqueous solutions; and HgI_2 and $HgBr_2$ photolysis and wave-packet dynamics of the fragments. He also initiated time-resolved structural studies of these systems by picosecond X-ray diffraction at the European synchrotron radiation source in Grenoble and worked on numerous other systems, such as iron carbonyl, silver in a rare-gas matrix, colloidal gold, and C_{60}.

Two-dimensional infrared spectroscopy

Researchers developing new techniques of ultrafast nonlinear optical spectroscopy had long envied the NMR community's ability to create spectroscopic correlation maps revealing interactions and, thereby, spatial information. But the difficulties of extending 2D NMR methods into the optical region seemed formidable. Robin's demonstration of 2D infrared spectroscopy in 1998 (48) opened up a new chapter for optical spectroscopy. 2D spectroscopy covering the Terahertz to the ultraviolet is now being pursued by an estimated 50-70 groups worldwide. Robin's original experiments used a narrow-band

tunable infrared pump, and a broadband IR probe pulse. This is equivalent to the NMR double-resonance experiment and the application to the amide modes of three peptides (48) showed how the couplings between amide modes and their frequency distributions could be obtained, pointing the way to structure determination via 2D IR spectroscopy. Robin soon used this approach to determine the structure of a cyclic pentapeptide in solution (49).

Two more developments were needed to create the phase-locked 2D IR spectroscopy in common use today—photon echo configuration (50) and heterodyne detection (51). The experiment now is analogous to NMR correlation spectroscopy (COSY) and nuclear Overhauser effect spectroscopy (NOESY) experiments. Robin went on to introduce "two-color" 2D IR, analogous to heteronuclear NMR (52), and chemical-exchange 2D IR. This latter method enables the determination of the ultrafast (picosecond) dynamics of systems at equilibrium undergoing thermal chemical events, such as hydrogen bond breaking or making, as was described in Robin's initial paper (53). That all these developments took place within a 5-year period is testimony to Robin's brilliance, drive, and boundless curiosity.

Applications in biophysical science

In the last two decades of his life many of Robin's applications of 2D IR were concerned with the structure and dynamic of peptides and proteins (54). His interest in applying new developments in spectroscopy to these molecules actually began in the '60s, at a time when there were hardly any studies on biomolecules by scientists in the chemical physics community. His interest in proteins started with a polarized-absorption study of single crystals of heme proteins (1, 55, 56). Two factors attracted Robin to these experiments. He admired John R. Platt, whose theoretical work stimulated his interest in porphyrins. In addition, heme protein crystals provided an example of a near-perfect oriented gas of chromophores, as the interactions between the heme groups are extremely weak due to the large distances between hemes that are embedded in the interior of a much larger molecule. Not only did Robin use the results of a study he made of cytochrome *c* crystals to interpret the electronic origin of a widely studied conformationally sensitive absorption band, but the information on the orientation of the heme group from the planar absorption of polarized light by the porphyrin pi electron system was helpful to X-ray crystallographers in interpreting the first electron-density maps of cytochrome c. Robin was fond of pointing out that his 1967 paper in the *Journal of Chemical Physics* (55) was the only paper in the journal that year concerned with a protein.

Robin's major contributions to protein physical chemistry began with his studies on the picosecond photodissociation of ligands from the heme group in hemoglobin and myoglobin. Using the Nd glass laser, which often took weeks to align because of its painfully low repetition rate of ~ 0.01 Hz, he recorded the first picosecond-resolved multi-wavelength absorption spectra (57). This work resulted in his discovery of geminate recombination of oxygen and nitric oxide (58, 59). His observation of the sub-picosecond rebinding of oxygen—observed but not interpreted as such in ref. (57)—was among the first observations of geminate recombination at ambient temperatures. Both ligands show much faster geminate recombination than carbon monoxide, which Robin pointed out could be due to electronic in addition to steric factors because the reaction is associated with a smaller change in spin angular momentum. These experiments initiated the new sub-field of research in physical chemistry of time-resolved spectroscopy of proteins, a field that flourishes to this day.

Robin followed his optical studies with his development of femtosecond-resolved infrared spectroscopy, which took the connection of ligand motion and protein dynamics to a new level (60). By monitoring the vibrational spectrum of carbon monoxide, he showed that the ligand photodissociates in less than 300 fs and remains in a pocket in the protein next to the heme iron for at least a nanosecond, a finding that has recently been verified by direct observation in picosecond-resolved X-ray crystallographic studies by his former post-doctoral fellow Phil Anfinrud and coworkers (61). The experiments also produced some of the first experimental information on the dissipation of heat into the protein and surrounding solvent from the energy of the laser pulse deposited in the heme in excess of what is required for photodissociation. Understanding the dynamics of cooling following laser excitation (62, 63) was largely fueled by Robin's suggestion, in one of the first atomistic molecular-dynamics simulations of a non-equilibrium experiment, that transients in many ultrafast optical experiments resulted from laser heating (64).

Robin also made important contributions to the field of protein folding, where he was the first to apply the technique of laser-induced temperature jump (65). This method has subsequently turned out to be the most powerful kinetic method in the protein-folding field, allowing the study of fast processes such as alpha helix formation, as well as kinetics studies of the very-fastest-folding proteins. Another example of where Robin was there first pointing the way for others was in the study of protein folding using single-molecule spectroscopy (66, 67). In these studies, his primary goals were to measure the dynamics of an unfolded protein and to observe a protein undergoing reversible folding-unfolding

transitions from measurements of Foerster resonance energy transfer (FRET). Although he did not quite achieve that, these experiments sparked the interest of many labs around the world in exploiting the power of single-molecule FRET for the study of protein folding. Robin was also the first to apply single-molecule spectroscopy to light-harvesting complexes (68, 69).

Robin opened up yet another new area by showing that spectra, polarization character-istics, and excited-state lifetimes could be measured for single pigment-complexes even at room temperature. His work led to the realization that spatial and electronic structures and excited-state dynamics of light-harvesting complexes fluctuate in time. This sensi-tivity to structural change, leading to the introduction of trap states, provided important insights into the mechanism of the ubiquitous but still poorly understood process of photoprotection or nonphotochemical quenching in plants.

Very soon after his invention of 2D IR spectroscopy, Robin saw the potential of applying this new technology to the investigation of the structure and dynamics of peptides and proteins (54). Previous time-resolved Raman and infrared studies of these systems relied on empirical correlations to obtain three-dimensional structures, in contrast to Robin's 2D IR, which not only yields structure directly, but does so at any time scale of interest with an intrinsic time resolution of less than 1 ps (70). One of the first applications was the investigation of the structure of a cyclic peptide (49). Robin demonstrated the power of the method for biophysical applications in his subsequent study of the alanine dipeptide; this study appears to have settled a long-standing controversy by showing that this benchmark peptide for molecular-dynamics simulations has an extended (polypro-line-II) conformation (71). Robin's studies on a series of peptides showed that 2D IR is also capable of obtaining information on the distribution of structures and dynamics of individual residues (72). His work on the amyloid fibrils of Alzheimer's disease is particularly noteworthy; through the interaction of water with the amide modes of the polypeptide backbone, Robin's two-dimensional spectra reveal both the location and dynamics of water molecules within the fibrils (73, 74).

One final example of Robin's creative research in biophysical science is his invention of a novel super-resolution optical-microscopic technique, which he named PAINT (points accumulation for imaging in nanoscale topography) (75). Robin's technique was simple and beautiful, and developed completely independently at the same time as the other super-resolution methods based on photophysical properties of fluorophores. In his method the object to be imaged is continuously targeted by fluorescent probes that

exhibit a large change in quantum yield upon binding to produce a diffraction-limited fluorescent spot on the object. As in other super-resolution methods, the location of the fluorescing single molecule is determined with very high precision by fitting the emitted intensity distribution to the 2D parameters of the point-spread function. In this way the object of interest is "painted" with the fluorophore probe at nanometer resolution.

A life in retrospect

Robin left his mark on science not only through his own original research but also by inspiring and creating many scientific opportunities for others. He possessed a larger-than-life personality and an immense intellect that was a major force in the lives of several generations of scientists. As a faculty member at the University of Pennsylvania for 50 years, he trained 75 Ph.D. students, including Nobel Laureate Ahmed H. Zewail, and more than 90 postdoctoral fellows. Robin's influence on the whole scientific community was extraordinary, often challenging colleagues through insightful questions, inspiring them to think more deeply and to do even better work. A glance at Robin's publications reveals an astonishing range of topics and consistency in setting new benchmarks. His 10 most-cited papers were written in the 1960s, '70s, '80s, '90s, and 2000s!

A lively personal recollection of Robin's scientific life was published in 2006 in the Annual Reviews of Physical Chemistry (1). On the occasion of his 65th birthday, a special issue of the Journal of Physical Chemistry, edited by William A. Eaton, H. Peter Trommsdorff, and Ahmed Zewail, was dedicated to him (2). A special issue of *Chemical Physics*, edited by Peter Hamm, Zewail, and Graham R. Fleming, was dedicated to Robin upon his retirement as editor in 2012 (3).

For 37 years (1975 to 2012) Robin was editor of *Chemical Physics*. Beginning in 1971 he was director of the Ultrafast Laser Research Resource, and in 1978 he became the director of the Regional Laser and Biomedical Research Laboratory, sponsored by the National Institutes of Health for the development and application of advanced laser technologies to problems in biomedicine. His other professional positions included visiting professorships at universities in Cambridge (UK), Canberra, Pasadena, Munich, Oxford, Paris, and Grenoble. He was chair of the John Scott Advisory Panel for the City of Philadelphia from 1988 to 2010. In June 2013 Robin was awarded, post mortem, a D.Sc. (Honoris Causa) degree from the University of Edinburgh.

Robin's contributions were recognized through numerous honors and prestigious awards. These included the Linus Pauling Award (2012), Pittsburgh Spectroscopy

Award (2010), honorary fellow of the Royal Society of Edinburgh (2008), A. H. Zewail Award in Ultrafast Science and Technology (2007), F. Albert Cotton Medal from Texas A&M University (2005), Benjamin Franklin Medal in Chemistry (2003), Centenary Silver Medal of the Royal Society of Chemistry (2000), E. Bright Wilson Award in Spectroscopy (1998), Ellis Lippincott Award of the Optical Society of America (1997), LICOR Award, University of Nebraska (1996), Peter Debye Award in Physical Chemistry (1996), National Institutes of Health Merit Award (1990-2000), Philadelphia Section Award of the American Chemical Society (1990), Optical Society of America, Fellow (1989), SPIE Special President's Award (1986), Heriot-Watt University D. Sc., (Honoris Causa) (1984), fellow of the American Academy of Arts and Sciences (1982), member of the National Academy of Sciences (1982), Bourke Medal of the Faraday Society (1981), Alexander von Humboldt Senior Fellow (1978), American Physical Society Fellow (1978), John Simon Guggenheim Fellow (1972), Alfred P. Sloan Foundation Fellow (1962-1967), and Courtauld Scholar (1952-1955).

Personal recollections of Robin by the authors

W.A.E.: I met Robin for the first time in the spring of 1966 in the Deck Bar at 34th and Walnut Streets in Philadelphia, where he and two assistant professors, Alan Adler and Joe Higgins, often met to have a beer and argue vigorously about the relative importance to science of thermodynamics, statistical mechanics, and quantum mechanics. I had graduated from Penn medical school and was pursuing a Ph.D. in the laboratory of Philip George of the Chemistry Department, working on the thermodynamics of protein reactions. Robin's research at that time focused on the spectroscopic properties of molecular crystals. At one after-dinner meeting at the bar, when I told him that I knew about a structurally sensitive optical absorption band of an iron-porphyrin containing protein called cytochrome c and that I had in my possession a giant crystal of this protein—a gift from Emanuel Margoliash, who first crystallized this protein—he insisted on making spectral measurements on the crystal immediately, even though it was getting close to midnight. After performing a makeshift experiment, Robin excitedly announced to me that the near-infrared absorption band I had told him about was polarized perpendicular to the porphyrin plane and that no one had ever seen that before in this kind of chromophore. Robin gave a very impressive talk on this result just two weeks later at an international meeting at Britton Chance's Johnson Foundation in June of 1966. Both events, the experiment and the talk, dramatically changed the course of my scientific career. I left my rather unexciting experiments in calorimetry and potentiometry, which Robin

referred to as "stone-age" science, and joined his research group in the Laboratory for Research on the Structure of Matter building at 33rd and Walnut.

After just a few weeks in Robin's lab, his tremendous intellect, infectious enthusiasm, and continuous encouragement turned what had been for me a genuine interest in science into a permanent and intense passion for it. He did the same over the years for many other young people.

It was just one of his many great qualities. We very quickly became close personal friends. I introduced Robin to the world of proteins, and he introduced me to the excitement of forefront scientific research. He and I found that we had many interests in common outside science, and our respective wives, Carol and Gertrude, also became good friends. For the next 47 years, our families remained very close. We traveled to Europe together and for many years owned a house together in the mountains of Western Maryland next to Deep Creek Lake, where our families spent summer and winter vacations together.

What attracted so many people to Robin is that, in addition to being an incredibly smart and one-of-a-kind person, he had a fabulous sense of humor. He had a ton of charisma and did everything with great gusto, whether it was watching or playing sports, playing bridge, discussing politics, describing the dogfights between the RAF and Luftwaffe over the Firth of Fourth next to Edinburgh when he was a boy, or playing chess with his grandson, Finnian. Robin was a very good tennis player and extremely competitive on the court. During one period in the 1980s, when David Chandler was on the faculty at Penn before he moved to UC Berkeley, there were many doubles matches with Robin and John Trout, Robin's graduate student at the time, against David and me. In addition to being a world-renowned theoretical chemist, David is one of the very best tennis players in science, but Robin liked to win and always insisted on playing with John, who was a professional player with an international ranking before he came to Robin's lab. David was frequently quite annoyed with me because he believed that if I played just a tiny bit better we would win. Our only victory was a game on the court at David's home that started at 9:00 in the morning after John's graduation party at Robin's house, where at midnight I introduced John to a new drink for him—cognac!

Dinner with Robin was always a special event. He knew a great deal about food and wine and was truly a gourmet chef. One brief anecdote is objective evidence of his fine palate. In 1988 Robin was on sabbatical leave in Paris, and he and I made a one-day trip to the Champagne country, stopping at various vineyards to sample their champagne. A stop at one small vineyard near Epernay was the most interesting. The champagne was called "Jeeper" (http://www.champagne-jeeper.com/) because the father of the current owner of the vineyard had received a jeep from the American army as a reward for being part of the French Resistance. Robin was making such insightful comments to the owner, *in French*, that the owner

Robin and Bill Eaton, 1997.

kept offering Robin better and better quality champagne. The owner was so impressed with what Robin had to say about each sample that he asked him if he could hire him as a taster for the critical step of adjusting the sweetness of the champagne just before the final corking of the bottles. Robin was really tempted and for a moment he actually considered accepting the job.

There was never a dull moment with Robin, and I witnessed all sides of him, both professionally and personally. He loved his research and he loved the University of Pennsylvania. He was a teacher not only of students and post-doctoral fellows at Penn, but also of established scientists. What was so unusual about Robin is that he was still developing state-of-the art technology and producing groundbreaking research into his 80s. He barely slowed down, even though he knew he had a terminal illness. This is not just an opinion; the objective record shows that unlike almost any other scientist at his age, the number of citations to his publications *per year* was still on the rise at his death. Just two weeks before he died, Robin was telling me with great excitement about ideas he had for new experiments.

G.R.F.: There are many scientists who add new ideas and techniques to an individual scientist's store of knowledge, but very few who enrich one's whole life. Robin was one such. He was a true scientific hero of mine. His work and friendship were a constant inspiration to think more deeply and do better work. Whenever I spoke at a conference that Robin was also attending, he always asked me the deepest and most difficult question. At first this was pretty scary, but I soon came to appreciate that these questions (which I often didn't do so well at answering!) would lead me to better understand my own work and sharpen my own questions.

By striking out into the new field of ultrafast spectroscopy when it was just being born, Robin changed the nature of spectroscopy. He realized well before others that moving to the picosecond and shorter timescales wasn't about just measuring faster and faster events, but also revealing and understanding the fundamental processes that underlay all condensed-phase chemical and biochemical phenomena. Robin went on to apply his techniques, especially those involving infrared ultrashort pulses, to biophysical problems, especially peptide and protein structure and dynamics. This went on at a time when it was far from fashionable for "real" physical chemists to study biological systems. In fact, Robin told me that one senior chemist, upon Robin's election to the National Academy of Sciences, said, "Well, you must have hidden your biophysics work." But Robin didn't follow fashion or fads, rather his own insatiable curiosity and intellectual agenda.

Robin always combined experimental virtuosity with deep theoretical analysis. Given that I came from an English academic education where theory and experiment seemed to be two separate fields, his approach was a great inspiration to me. Robin was also a generous, if generally unseen, mentor to younger scientists, both in science and in enjoying some of life's rewards, particularly food and wine. I know that Robin helped me in my early career in ways that he never mentioned, but I'd rather describe another kind of mentoring that continued for my whole career: Robin didn't like to admit that he didn't quite get something, and at one memorable dinner where we finished the first bottle of wine before even looking at the menu, I was left realizing that there were aspects of multi-level molecular coherence and relaxation that neither of us quite understood at that time, and this spurred me to begin studies that continue today of coherence in dynamical systems. But we didn't compete or try to own specific areas. Instead I believe we learned from each other (well, I certainly did from Robin).

In a field where generosity to others isn't always what it might be, Robin set the standard of thoughtfulness and decency. While holding to a very high research standards, he

was unfailingly kind and supportive to young scientists. He was a superb human being as well as a great scientist. The combination of Carol, another wonderful person, and Robin added greatly to life in Philadelphia. Dinner with them both (I'm also married to a Canadian) ranged over social issues in Philadelphia, politics in Vancouver, and international topics in a way I will miss very much.

Hochstrasser and Fleming families outside restaurant Helene Darroze in Paris circa 2003. From left to right: Jennie Hochstrasser, Robin, Carol Hochstrasser, Matthew Fleming, Graham Fleming, Jean McKenzie.

I mentioned food and wine—how could we not, in remembering Robin? He took me to my first Michelin three-star restaurant in Paris. It cost all of the expenses the conference had given me earlier that day, but it was worth it. Upping the ante to a rather crazy level at a conference on the French Riviera, Robin proposed that we try to average 1.66 stars

per day for a week. We failed (I think my average was 1.5 or so) but we had a hell of a time trying!

H.P.T.: In the early 1960s, as a thesis student, I first met Robin through his publications, which I studied diligently, because at that time he was clearly the most important scientist in the field of molecular crystals. Then in September 1971 I met Robin and Carol in person at the 6th International Conference on Photochemistry, in Bordeaux. I still remember vividly how Robin slammed a pile of manuscripts onto a table and remarked nonchalantly, "These are just a few papers we finished off last week." At a time when publishing one paper a year was considered a good output in France, this made quite an impression. I remember in particular one paper, which made a claim similar to that in a paper I had in press, namely the first observation of a magnetic dipole transition in a molecular crystal.

But Bordeaux was not only science; we had also very pleasant dinners together at Chateau Margaux and at la Corniche in Pyla-sur-Mer, near Arcachon. This was the beginning of our friendship, of scientific exchange, and of a very fruitful collaboration. The following year I visited Robin and Carol in Cambridge, where Robin spent a sabbatical leave with David Buckingham, and I was able to persuade Robin to be on my thesis defense committee later that year in Grenoble. I still remember the question Robin asked me after the thesis defense about the line-widths I observed in my spectra: for most condensed-phase spectroscopists at that time, broad lines were just a nuisance that limited the spectral resolution and not a source of important information about the dynamics. During the following dinner at a friend's house, a young lady, serving a big plate with a fish, accidentally poured the sauce down Robin's neck, but he acted with great dignity and feigned to have not noticed anything.

A year later, in 1973, I worked in Robin's lab and learned to appreciate his enormous talent as an inspiring teacher and mentor: he was able to create such excitement and enthusiasm that many students did their best work ever under his supervision. His door was always open and his discussions with students and post-docs came across as conversations among equals. I learned more about science and good style in science than I had learned in all the years before in Grenoble. Thanks to him I learned the importance of asking the right questions and never indulging myself with accepting nice-looking results, but instead asking what is really relevant and what it is we want to learn. I realized only later how deep his understanding was and how far ahead of the crowd he was.

The following year Robin came with his family for the first of many invited professorships at Grenoble. He had rented a house in Talloires in order to explore the cultural and culinary aspects of one of the nicest areas in France. At this time, he initiated the study of the phase transition in biphenyl by neutron diffraction at the new Institute-Laue-Langevin. In the following years, we shared a NATO grant that enabled me to

Robin and Peter Trommsdorff, 2007.

come more frequently to Philadelphia. I stayed with Robin and Carol and enjoyed their hospitality: one important evening project during the summer of 1977 was building a backyard barbecue using mortar bought daily on the way home and bricks left over from the building of the house at Society Hill. Robin even managed to acquire a covering veneer of granite tiles from a stonecutter who had previously worked at the Vatican. But we also worked in the lab and developed non-linear optical experiments such as multi-resonant 4WM. Already then, as I realized only later, Robin saw the full potential of these experiments and had the vision that later led to his development of 2D-IR spectroscopy.

During this time we went to Bordeaux for a thesis defense for one of my students, and Robin gave a seminar in French, as his French was by then much better than the English of the audience. We also visited the Saint-Emilion vineyards, and Robin suggested that we invest our NATO grant money in wine from Château Cheval Blanc, a Grand Cru Classé (http://www.chateau-cheval-blanc.com/fr). Unfortunately, being too honest, we

used our own money for only a few bottles. The investment of the grant would have resulted in a fabulous return!

Our exchange and scientific collaboration continued, and I enjoyed working on many more projects with Robin. One of my more important contributions was bringing wine and cheese from France to Philadelphia, and I once even brought an evacuated glass-metal optical cryostat as carry-on luggage—unthinkable today.

Being with Robin was inspiring and exciting. He was always ready for new adventures and willing to explore and to learn about new areas regarding all aspects of life and culture. Guided by his excellent taste, I learned much more than science from him—for example, how to bake a wild Salmon wrapped in a newspaper in an open fire and which whisky to drink and how.

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