History of Science

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Michael Kasha: From Photochemistry and Flowers to Spectroscopy and Music

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history of science · Kasha, Michael · photochemistry · singlet oxygen

Preface

Michael Kasha (Figure 1) was a brilliant scientist with unique and diverse achievements, and an outstanding personality who was driven by intense curiosity to address the basic laws of nature by accumulating and connecting scientific knowledge gathered through scrupulous experiments and theoretical methods in different areas. Kasha, who passed away on June 12, 2013, at the age of 92, was a "renaissance man",[1] who connected chemistry and physics with music, photography, the color of daylily flowers, and astrochemistry. He was a key founder of modern photophysics, photochemistry, and molecular spectroscopy in condensed phases.

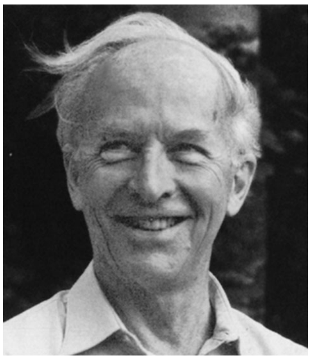

Figure 1. Michael Kasha (1920–2013).

Kasha started his research career in the 1940s under the supervision of Gilbert N. Lewis, and formulated a fundamental law connecting fluorescence and phosphorescence through intersystem crossing.[2] Lewis and Kasha concluded that the phosphorescent state they found in all sorts of molecules, complex or simple, organic or inorganic, is the triplet state. Furthermore, Kasha's rule, which determines the energetics of electronic transitions of molecules, that is, the emitting electronic level of a given multiplicity is the lowest excited level of that multiplicity,[3] can be found in any textbook of physical chemistry or molecular spectroscopy. He also showed that interaction with heavy atoms could permit observation of singlet–triplet absorption and phosphorescence emission in organic molecules—named the "external heavy-atom effect" or the "Kasha Effect".[4] It was he who combined the quantum mechanical theories of excitonic and inductive-resonance excitation energy transfer.[5] He discovered that singlet oxygen could be produced in chemical reactions and studied the chemiluminescence of molecular oxygen,[6] the great importance of which in biology was recognized in later research. He also explained the role of antenna pigments in photosynthesis.[7] He was a pioneer in the studies of different systems that exhibit excited-state proton transfer—intramolecular, biprotonic, and solvent-mediated.[8] He constructed the four-level diagrams of these processes and proved their connection with the electronic charge transfers. Any one of these discoveries, and there were so many of them, would have been enough to earn him a place in the history of science. In this Essay, we use our own personal recollections to add to biographical material[9] in order to answer the question: who was this person with so many outstanding contributions?

Biography

Michael Kasha was born on December 6, 1920, the son of Ukrainian immigrants, in Elizabeth, New Jersey (USA). He came from a simple, poor family who had moved together with a whole village from the Carpathian region of Ukraine in hope of a better life. His first education was at a church

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school, where Ukrainian was the language of instruction. At that time, Michael was probably the only person in the large local Ukrainian community who managed to continue his education. In junior high school, his physics and chemistry teacher, as well as teachers of other subjects, supported his outstanding abilities and talents and encouraged him to continue his education in high school. But his father, who was struggling hard to make ends meet, insisted that he take up a practical profession, so while attending high school, he also trained to become an electrician. Soon after, he found a job at the Pure Research Division of the Merck Chemical Co. at Rahway, as a lab boy in the group of Dr. Karl Folkers, and soon became his personal assistant. Folkers, who later became one of the world's most famous pharmacological chemists, claimed that he has "discovered" the latent talent in the 17-year-old high-school graduate, who showed extraordinary initiative and abilities. He continued his education by traveling every night to New York City to attend evening classes at the Cooper Union Engineering School.

After two years of work and evening studies, supported by Dr. Folkers' kindness and persuasion, exciting new scientific results encouraged Kasha to take up regular chemistry studies at the University of Michigan. His dream was to work with Gilbert N. Lewis, a brilliant chemist, who was active in many areas, including thermodynamics, valence theory, and the electronic theory of acids and bases.[10] Kasha's dream was realized in February 1943, when he obtained his BS in chemistry and moved to the University of California at Berkeley.

At Berkeley, Lewis and Kasha started their work on the triplet-state origin of phosphorescence. The research on his PhD thesis was complicated by Kasha's recruitment along with other young qualified chemists to work in the Plutonium Chemistry Project, part of the Manhattan Project, in the years 1944–1948, spanning World War II and the early postwar period. They had to enrich plutonium, working all day barehanded without any protection. For this reason, time for experiments on his PhD thesis was limited to after-work hours and weekends. Despite such tremendous pressure, he succeeded in finishing his research on time, and in February 1945, he was awarded his PhD on the basis of his work entitled *Triplet States of Organic Molecules*.

In 1948, Michael Kasha married Lilli Cohn, a linguist specializing in far-eastern languages. They lived a happy life together for 65 years. From 1949–1950, Michael carried out postdoctoral research in the laboratory of Robert S. Mulliken (Nobel Laureate in Chemistry in 1966) at the University of Chicago and 1950–1951, he worked as a lecturer at Manchester University in England. In 1951, against strong competition, he obtained the position of Professor of Chemistry at Florida State University (FSU) in Tallahassee.

Michael and Lilli Kasha settled in a house built on a large estate, surrounded by forest and extending to a wild lake near Tallahassee, where they stayed until the end of his life. Over the years that followed, he put a lot of effort into preserving the unique natural environment of Florida, and even wrote a book on the subject.[11a]

Florida State University became his permanent place of work, where, apart from fulfilling scientific and teaching duties, he also held a number of administrative positions. From 1959–1962, he was the Chairman of the Chemistry Department, and in 1960, he founded the Institute of Molecular Biophysics of which he was the Director from from 1960–1980 and also took special care of during the whole period of his professional activity.

In 2005 (on the occasion of his 85th birthday), his home university instituted a new research unit, the Kasha Laboratory, which is a group of research units from the departments of Physics, Chemistry, Biochemistry, Mathematics, Computer Studies, and Engineering, as well as the Institute of Molecular Physics. In 1995, Kasha funded an annual award in his name for postgraduate students who, apart from obtaining excellent results, also had original scientific publications resulting from work carried out in the Institute of Molecular Biophysics.

During his several decades of scientific activity, Kasha published over 200 original works, a huge portion of which had a fundamental importance for photochemistry, molecular spectroscopy, physical chemistry, and biophysics.[9] The numerous citations of Kasha's works in original publications and monographs published by other authors prove how important and fundamental these works are for the above-mentioned fields as they encompass broad areas of physics and chemistry.

Kasha's scientific activity was surprisingly combined with music. He suggested redesigning the traditional classical guitar based on his scientist's view as a problem of three coupled oscillators: the vibrating sound board, the real string, and the cavity resonator.[1,11b] As a result, the string instruments that did not evolve for about 300 years got a new unprecedented sound. The effectiveness of the new design was recognized by top musicians who used the new instruments in their concerts. He also initiated the creation of a anechoic (echo-free) chamber for acoustic research at the Department of Music Studies at Florida State University.

The Triplet-State Origin of Phosphorescence

In 1944, Kasha and Lewis published a work that was of fundamental importance for the development of modern molecular photophysics, as well as for that of photochemistry and photobiology. In that work "Phosphorescence and the Triplet State", they suggested the triplet state theory of phosphorescence.[2] It was already known that organic dyes may exhibit intense phosphorescence in cryogenic matrices, but this emission was not attributed to the individual molecules, but rather to aggreagated forms and impurities, despite the fact that it was observed for dyes adsorbed on solid matrices. There was a general notion that the triplet states of molecules could not be accessed after excitation by light. Moreover, the quantum mechanical calculations of Sponer and Teller[12] indicated the impossibility of the singlet–triplet transition for molecules composed of atoms with small atomic masses (C, N, O). Scientists tried to find a connection between fluorescent and phosphorescent emissions, and in the "Jabłoński diagram", introduced into the literature in a famous work by Aleksander Jabłoński published in *Nature* in 1933,[13] a crucial role was attributed to the "metastable state", whose nature had been a matter of much debate and controversy. It was the work of Kasha and Lewis from 1944, in which the results of their own phosphorescence and fluorescence studies for many organic compounds were interpreted on the basis of the Jabłoński diagram, that led to the conclusion that the metastable state “M” was actually a triplet state. In 1945, Lewis and Kasha reported the essence of the quasi-forbidden singlet–triplet absorption in molecules, corresponding to the phosphorescence emission band.[14] This paper can be understood as a seminal contribution to the photophysics and photochemistry of the electronic transitions in singlet–triplet absorption and emission. It stated that phosphorescence originates from a singlet–triplet transition (or intersystem crossing) in the excited state (Figure 2).

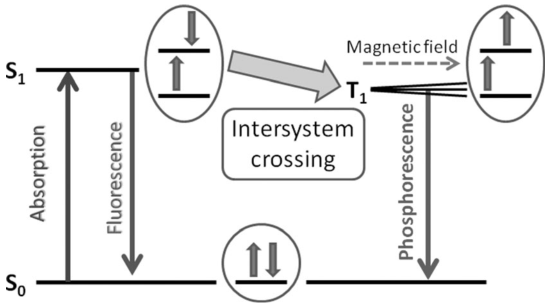

Figure 2. Intersystem Crossing, the change of electron spin in the excited state from singlet (S_1) to triplet (T_1), as the origin of phosphorescence. The triplet nature of the phosphorescent state is revealed upon the application of a magnetic field, resulting in splitting into three energy levels.

The theory of phosphorescence from the triplet state was not immediately accepted by the international community of photophysicists and photochemists. For more than a decade, this issue was the focus of heated debate at scientific seminars and conferences, and in papers published worldwide. After the sudden death of Lewis in March 1946, the 25-year old Kasha stood alone to defend the triplet-state theory in intense discussions, responding to critical comments of such prominent scientists from different fields as James Franck (the physicist connected to the Franck–Condon principle) and Robert S. Mulliken (a molecular spectroscopist and quantum chemist), as well as Eugene Rabinowitch (a photobiologist) and Robert Livingston (a photochemist). The essence of this criticism was that singlet–triplet transitions are forbidden by quantum mechanical rules. As was indicated later,[15] it was not the quantum mechanics that was divergent; it was the ultrafast excitation dynamics of polyatomic molecules that led the intersystem-crossing rate to overcome the million-fold restriction against singlet–triplet excitation in molecules containing low-atomic-weight atoms (C, N, O). These observations were summarized in a classic Review.[15]

Finally, a major breakthrough allowed this hypothesis to be generally accepted. This came from crucial experiments carried out in 1958–1959 by Hutchison and Mangum,[16] as well as those by van der Waals and de Groot[17] who, by using electron paramagnetic resonance, observed the splitting of the metastable state in a magnetic field into three sublevels, which was direct proof of the triplet character possessing a spin $S = 1$ and hence being paramagnetic (photomagnetism).

The recognition of the triplet-state origin of phosphorescence allowed explanation of many mysterious features of this phenomenon, such as the high quantum yields observed in low-temperature matrices and the lack of dependence of these spectra on the molecular environment. Evidently, the seminal studies of Lewis and Kasha opened the door to new fields of spectroscopic research, such as room-temperature phosphorescence, delayed fluorescence, flash photolysis, and optically detected magnetic resonance.

The External Heavy-Atom or Kasha Effect

Whilst establishing the triplet-state origin of phosphorescence, Kasha realized that according to the novel quantum-mechanical theories of his times, the strictly forbidden transition between singlet and triplet states might be broken down by incorporating the corresponding orbital angular momentum, namely by spin–orbit coupling. Kasha then turned his attention to exploring efficient methods for inducing the singlet–triplet transition by enhancing the spin–orbit interaction. This could be done by either increasing the atomic number or executing a large change of angular momentum during the singlet–triplet transition. Working with his postgraduate students, Kasha initially proved experimentally and theoretically that the presence of a heavy atom, either as a substituent in a molecule or an element in a solvent, influences significantly the probability of $S_1 \rightarrow T_1$ nonradiative transitions and the $S_0 \rightarrow T_1$ radiative transition (Figure 3); the latter could be observed through the $S_0 \rightarrow T_1$ absorption at 77 K. Later, it was also evidenced by enhancement of the radiative decay rate constant of the phosphorescence. This observation is called the “external heavy-atom effect” or the “Kasha Effect”.[4,18]

According to Kasha, there are two main factors that lead to the enhancement of spin–orbit coupling and hence acceleration of $S_1 \rightarrow T_1$ nonradiative transitions with parasitic loss of S_1 state excitation,[3,20] resulting in reduction of the fluorescence quantum yield and enhancement of the phosphorescence:

a) Molecules with heavy-atom substituents such as Br, I, Se, Te, or chelation to metal ions such as La^{3+}, Gd^{3+}, Eu^{3+}, or Lu^{3+} show an increase in the rate of $S_1 \rightarrow T_1$ transitions. The associated mechanism is nowadays called the internal heavy-atom effect. An analogous effect is seen, for example, in the presence of Tl^{3+} ions in solution or in alkyl halide solvents, where the halogen atom acts as the effective heavy atom, so that the rate of the $S_1 \rightarrow T_1$ transition is increased in the order $I \gg Br > Cl$. This process is known as the external heavy-atom effect; such external quenchers have become important tools in the study of biological macromolecules[21] as they allow the study of surface topology by distinguishing the chromophore groups exposed to the surface and thus accessible to the heavy-atom quencher.

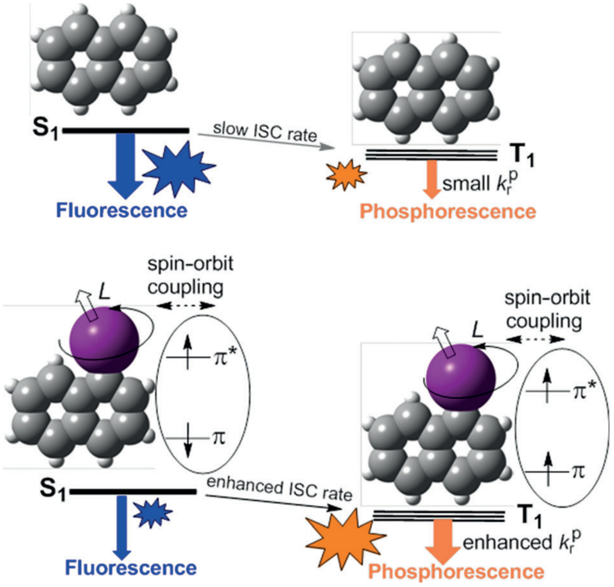

Figure 3. The heavy-atom effect (illustrated with naphthalene (top) and 1-iodonaphthalene (bottom) molecules).[19] The iodine atom possesses a strong spin–orbit coupling, resulting in the increase of both the rate of ISC and the efficiency of phosphorescence. k_r^P denotes the radiative decay rate constant of the phosphorescence.

b) Heteroatom groups, such as aza, nitro, nitroso, carbonyl, quinone in small aromatic molecules. These groups introduce the $n \rightarrow \pi^*$ excitation (the electron is promoted from the nonbonding lone-pair orbital to the π^* antibonding one),[3,20] leading to a great change of the orbital angular momentum, which then couples with the spin angular momentum to enhance the singlet–triplet transition.[22]

Classification of Electronic Transitions

The new fields of spectroscopy required a quantum-mechanical background, new concepts, and new terminology. In general, Kasha's experiments focused on a widely understood introduction of one-electron orbital theories to explain a great number of physicochemical phenomena that were observed in absorption and emission spectra. Based on the theory of one-electron orbitals in organic and inorganic molecules, Kasha suggested that molecular electronic transitions could be classified into three kinds, $\pi \rightarrow \pi^*$, $n \rightarrow \pi^*$, and $l \rightarrow a_{\pi}$.[3] This classification of electronic transitions proved to be extremely useful for the systematic analysis of huge amounts of information on the spectroscopic behavior of organic and polyatomic inorganic molecules.[20, 23–25] It introduced a common language for spectroscopists that is still in general use. A natural description of the mechanisms of excitation of molecular associates in the form of dimers, excimers, polymers, and lamellar configurations was also provided.[26]

Kasha's Rule

Michael Kasha is perhaps most widely known for Kasha's rule, a statement formulated in 1950 that is of fundamental importance to the photophysics and photochemistry of excited molecules.[3] This rule states that photon emission (fluorescence or phosphorescence) occurs in appreciable yield only from the state closest in energy to the ground state of a given (singlet or triplet) multiplicity in the condensed phase.[27]

A molecule residing in its electronic ground singlet state S_0, upon absorbing a photon, may be excited to any of a set of electronic states higher in energy (denoted S_n where $n > 0$), depending on the energy of the absorbed photon. According to Kasha's rule, as a result of internal conversion to the lowest excited state, S_1, photon emission should proceed only from this state. Figure 4 illustrates the spectroscopic and energetic aspects of this rule. A similar result is observed for the triplet excited states, in which the phosphorescence originates from the lowest triplet state T_1.

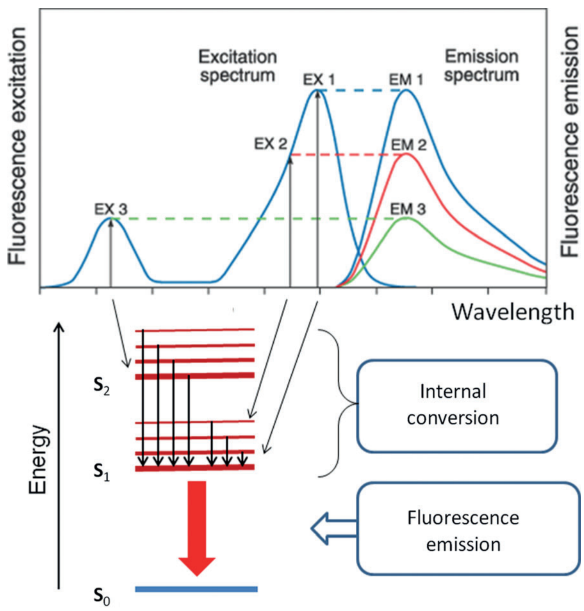

Figure 4. Illustration of Kasha's rule. When a fluorophore is excited at any of its energy levels, the fluorescence emission proceeds from the lowest vibrational level of the S_1 electronic state with an intensity proportional to the number of absorbed quanta. This effect arises from rapid internal conversion that precedes the emission. The upper diagram shows that excitations at different wavelengths lead to the same fluorescence spectrum. Fluorescence excitation should match the absorption spectrum, and, according to the Kasha's rule, the fluorescence-band intensity should not change in shape upon photoexcitation.

In a qualitative manner, the rule can be explained by the combination of two principles, so that the rate depends on the degree of overlap between their vibrational wavefunctions (Franck–Condon factor) and the density of accepting vibrational states (Fermi's Golden rule). The greater the overlap and the density of states, the faster the molecule can undergo transition from the higher to the lower electronic level. The overlap increases as the vibronic levels involved in the transition become closer in energy. In most molecules, congestion of the higher electronic states results in the vibronic levels of the excited states all lying close together. Molecules in the upper states possess a higher density of isoenergetic states in the energy-accepting site and undergo fast vibronic transition followed by collision-induced vibrational relaxation ($>10^{11}$ s^{-1}) to reach the lowest excited state, e.g., S_1 for the singlet manifolds, prior to any detectable emission taking place. Generally, the energy gap between the S_1 and S_0 states is greater than the gap between other adjacent states, which allows rapid population of the S_1 state, from which the fluorescence occurs on a longer timescale.[26b] Indeed, it was Kasha who rationalized that internal conversion and intersystem crossing are nonradiative transitions between the same and different spin states, respectively. The validity of Kasha's rule was proven in many experiments on different fluorophore systems. In the meantime, a number of exceptions that "prove the rule" became known. The classic example of "anti-Kasha" fluorescence is azulene, and the peculiarity of its fluorescence was studied by Kasha himself.[28] In this molecule, there is a large energy gap between the S_1 and S_2 excited states and thus fluorescence from the S_2 state is more favorable than internal conversion from S_2 to S_1. On the other hand, Kasha's rule showed its validity in a much broader scope of photochemical reactions—upon excitation to high-energy states, internal conversion proceeds rapidly and the photochemical transformations start from the lowest excited S_1 state. Thus, the extension of Kasha's rule can be formulated as follows: "Polyatomic molecular entities react with appreciable yield only from the lowest excited state of a given multiplicity".[29]

Since only one state in a polyatomic molecule is expected to produce appreciable emission, the empirical Vavilov law, "The quantum yield of luminescence is independent of the wavelength of exciting radiation", follows directly from Kasha's rule (and is sometimes referred to as the "Kasha–Vavilov" rule).[29]

The Generation and Photochemistry of Singlet Oxygen

The discovery of singlet oxygen and of its generation in chemical, photochemical, and biochemical reactions was an extremely important finding in chemistry and biochemistry. In 1963, Khan and Kasha reported that the product of the reaction of alkaline aqueous hydrogen peroxide with sodium hypochlorite was in fact singlet oxygen.[6] They proved experimentally that singlet oxygen molecules ${}^1O_2^*({}^1\Delta_g)$ can collide to form a transient dimer ${}^1O_2^*$–${}^1O_2^*({}^1\Delta_g$–${}^1\Delta_g)$ that emits red light ($\lambda_{max} = 633.4$ nm). The phenomenon of such emission (chemiluminescence) accompanies a number of chemical redox reactions (e.g., $H_2O_2 + OCl^- \rightarrow {}^1O_2^* + H_2O + Cl^-$).[30] Furthermore, the excited triplet state of photosensitizers allows the generation of singlet oxygen by energy transfer (Figure 5).

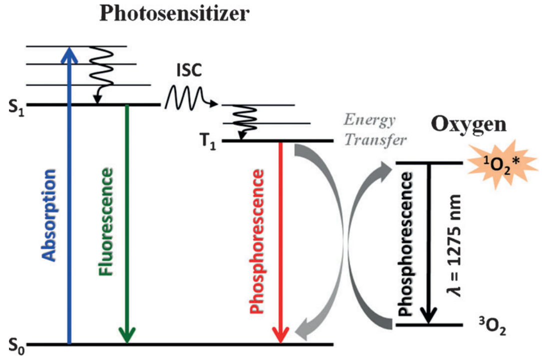

Figure 5. Generation of singlet oxygen ${}^1O_2^*$ in a photochemical reaction. The photosensitizer dye is excited to the S_1 state and exhibits intersystem crossing (ISC) to the T_1 state that can either generate phosphorescence or transfer the excitation energy to the ground-state triplet oxygen ${}^3O_2$ to result in the excited ${}^1O_2^*$ state. The latter can emit phosphorescence in the near-IR region or undergo different photochemical processes.

It was shown later that singlet oxygen is a reactive and unstable molecule O_2^* (which represents the two low-lying ${}^1\Delta_g$ and ${}^1\Sigma_g^+$ states of singlet oxygen) that appears in the reactions of biological oxidation and is metabolically connected with the action of peroxidases.[31] Alternatively, singlet molecular oxygen can be generated by the collision between electronically excited dye molecules in the triplet state and ground-state molecular oxygen (which is a triplet state with the molecular term symbol ${}^3\Sigma_g^-$). Dexter-type energy transfer then takes place in this collision-induced complex, producing singlet molecular oxygen according to spin correlation and conservation.[32] Use of singlet oxygen in photodynamic therapy and other developments are discussed in a Review.[33]

The Study of Molecular Excitons

Albert Szent-Györgyi drew Kasha's attention to an interesting paradox: In solid matrices, dyes such as acridine orange emit phosphorescence, whereas in solutions, they emit only fluorescence, which contradicts the quantum theory of spin–orbital effects.[9] McRae and Kasha[34] studied these issues in detail and demonstrated that these effects can be explained by the theory of molecular excitons.

Starting in 1959, Kasha and his co-authors began reporting on the molecular exciton theory and on its application to molecular associates. The notion of the exciton had been introduced in 1931 by Yakov Frenkel[35] to explain the excitation of atoms in the lattice of insulators. He proposed that this excited state would be able to travel in a particle-like fashion through the lattice without the net transfer of charge. This mechanism was used to explain the transformation of electromagnetic radiation into heat in argon crystals. In 1948, A. S. Davydov further developed the exciton model, which explained the electronic states of naphthalene crystals.[36] Kasha's studies on molecular excitons were extended to hydrogen-bonded dimers, simple polymers, dispersion-force aggregates, and lamellar molecular associates, in which the intermolecular overlap between orbitals of two neighboring molecules is negligible. When two or more identical chromophores are incorporated into one molecular entity so that they are close to one another but without π conjugation, then the interaction of the transition dipole moments of the chromophores leads to two or more delocalized excited states for every local excitation of the single chromophore (Figure 6). This phenomenon is referred to as “exciton coupling”.

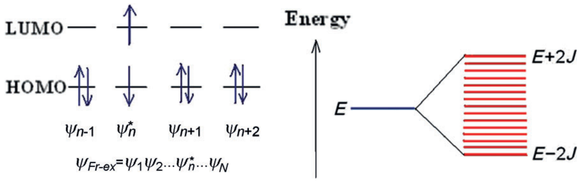

Figure 6. Excitons in molecular associates. Left: illustration of the Frenkel exciton neutral state created as the result of the transition of an electron from the highest occupied molecular orbital (HOMO) to the lowest unoccupied molecular orbital (LUMO). Ψ_i are the corresponding wavefunctions.[37] Right: Exciton-band energy diagram for a molecular associate with in-plane transition dipoles (J describes the dipole–dipole interaction). E is the electronic energy level of an isolated monomer.[38]

Kasha and his co-workers applied the theory of excitons to explain the splitting of electronic and vibrational states that are nondegenerate in a single molecule, and electronic transitions of noncrystalline composite molecules, such as linear molecular polymers (polyenes and others).[5,39] Within this model, the spectra of dimers and long polymers of simple and alternate translational structure, held by weak van der Waals or hydrogen bonding between the component molecules, have been explained. Within the molecular exciton formalism, the spectral properties of dye aggregates, in particular pyridocyanine parallel or card-pack dimers, hydrogen-bonded molecular dimers of diverse geometries, benzoic acid dimers and others, have been calculated. The exciton splitting in a simple dimer has been proven as a particular case of the “Davydov splitting”. These results were used to predict fluorescence quenching and phosphorescence enhancement for various polymers.

The molecular exciton model was used by Kasha to study some specific monomolecular lamellar structures.[38,40] The exciton-band energy level diagrams were calculated and the relation between exciton and conduction bands was studied for a variety of in-plane and out-of-plane arrangements of transition dipoles modeling the lamellar systems.[40] A quantitative comparison of the absorption spectrum of a monomolecular lamellar aggregate with that of the single molecule was also given and the dipole–dipole interaction sums were estimated in several cases to within an accuracy of two percent.

Kasha reported that exciton energy transfer takes place in hydrogen-bonded N-heterocyclic complexes, which can play the role of “energy sinks”[41] in carbon-glass solutions. The molecular exciton model was also used by Kasha to explain the mechanisms of excitation trapping and/or migration in molecular aggregates and polymers.[5,20a] Both types of these systems can be treated as weakly bound because of weak optical–electron interaction or van der Waals forces, respectively. These results are important, in particular, for understanding the Förster mechanism of the resonance energy migration by hopping between low-mass pigments in photosynthetic systems.[8]

Kasha showed that, in composite molecular systems, the exciton effects increase the rate of triplet-state excitation, thereby enhancing the phosphorescence of these materials. The exciton splitting in dimer and cyclic-trimer arrays of transition dipoles removes the excitation degeneracy only partially, thus decreasing the triplet excitation enhancement. This model successfully explained the total luminescence spectra of phenyl-substituted molecules and aryl amines in rigid glasses.[39b]

Proton Transfer Spectroscopy

Proton transfer, which is driven by the rearrangement of electronic systems in the excited state and usually involves a hydrogen bond, may occur as an intramolecular or intermolecular reaction. In some cases, more than one proton is involved in the overall transfer process. All these different cases were reported and formulated in Kasha’s pioneering works. Kasha and co-workers proposed a classification of phototautomerization phenomena based on different molecular mechanisms:[8,42] 1) intrinsic intramolecular proton transfer; 2) concerted biprotonic transfer; 3) static and dynamic catalysis of proton transfer; and 4) proton-relay transfer.

Of primary importance is 3-hydroxyflavone (3HF), a molecule that exhibits intramolecular excited-state proton transfer, manifested by the appearance of remarkable green fluorescence upon excitation with ultraviolet light, thus demonstrating a very large Stokes shift.[43] Kasha suggested the four-level diagram (Figure 7) to explain these excited-state transformations.

The genesis of the research that led to the discovery of excited-state proton transfer in 3HF is rather inspiring. It can be traced to Kasha’s hobby of gardening, in particular his deep and passionate interest in growing different cultivars of daylily (*Hemerocallis*), and hybridizing them to grow varieties with new morphologies and colors, with the eventual goal being to find a way to obtain a truly “blue daylily”. With this aim in mind, Kasha and his colleagues set out to separate and identify the flavonoids, which might be present in the methanolic extracts of the flower petals, using thin layer chromatography.[44] The observation of green–yellow fluorescence as the standard diagnostic test for flavonols (such as quercetin, fisetin, and kaempferol) upon excitation with a UV (365 nm) lamp appeared perplexing in view of the very large Stokes shift involved. To resolve this mystery, a detailed spectroscopic study was initiated on 3HF as the “skeletal precursor” of the flavonols, which led to the discovery of the occurrence of excited-state proton transfer in this and related flavonols.[43] This finding immediately resolved an unexplained spectroscopic anomaly, and perfectly exemplifies Kasha’s serendipitous research style, which he always tried to pass on to his students.

Further studies of 3HF and its derivatives allowed monitoring of the interplay between excited-state intramo-

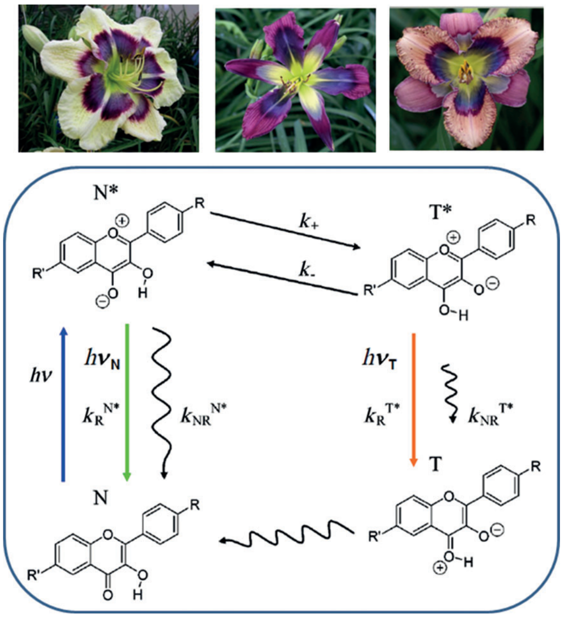

Figure 7. Top: Some typical varieties of Kasha's favorite daylilies with rich flower pigment color patterns, which triggered his interest on the spectroscopy of flavonoids. Bottom: The four-level diagram of excited-state proton transfer dynamics in 3-hydroxyflavones that are described by six kinetic constants. N: normal, T: tautomeric form of the flavone.

lecular proton transfer (ESIPT) and the intramolecular charge transfer (ICT) between the donor and acceptor sites in flavonols and other phototautomerizing molecules.[45] The thermodynamics and kinetics of the photoinduced tautomerization turned out to be extremely sensitive to solvent perturbations.[46] The interplay of ESIPT–ICT-coupled excited-state reactions raises a fundamental issue because the normal and proton-transfer tautomers interact differently with the polar environment, which creates a solvation-induced barrier that channels the overall proton transfer reaction. Nowadays, it is plausible to harness the normal-tautomer against the proton-transfer-tautomer emission intensity as a function of solvent polarity. Therefore, these molecules were proposed as protein-binding fluorescence probes[47] because of their great advantage of switching between two colors, arising from the interplay between the two emissive states. Since then, they have become valuable tools for studying not only the mechanisms of ESIPT–ICT-coupled reactions[48] but also the structure and dynamics in different molecular systems—from supercritical fluids to DNA, micelles, biomembranes, and living cells.[48a,49]

The 3HF molecule and flavonols in general fascinated Kasha and his students to the end. The last PhD thesis that Kasha supervised (by E. Falkovskaia) was also based on flavonols[50] and on the photophysical induction of dual fluorescence of quercetin and related hydroxyflavones upon intermolecular hydrogen bonding to the solvent matrix. Their biaxially symmetric covalently bonded derivatives demonstrate excited-state single or double proton transfer.[51]

The other important proton-transfer system discovered by Kasha was the dimer of 7-azaindole (7AI),[52] which was initially chosen as a simplified model of DNA base pairs (Figure 8). In the electronically excited singlet state, this doubly hydrogen bonded system undergoes an ultrafast tautomerization, measured even at cryogenic temperatures. Even though this phenomenon was reported in 1969, it still stimulates numerous (often quite heated!) discussions related to various aspects of the double-proton-transfer mechanism, in particular on the question of whether the two protons move in a stepwise or a concerted fashion. In contrast to other researchers,[53] Kasha always defended the concerted (one-step) mechanism, providing both experimental[54] and theoretical evidence.[55] Kasha emphasized that the two-step mechanism was not plausible owing to the excitonic nature of the 7AI dimer, as the excitation could not be localized just in one 7AI molecule. Tautomerization was also discovered in 7AI molecules hydrogen-bonded in a cyclic fashion to water or alcohols, which was also reported for the first time in a seminal paper by Kasha.[52]

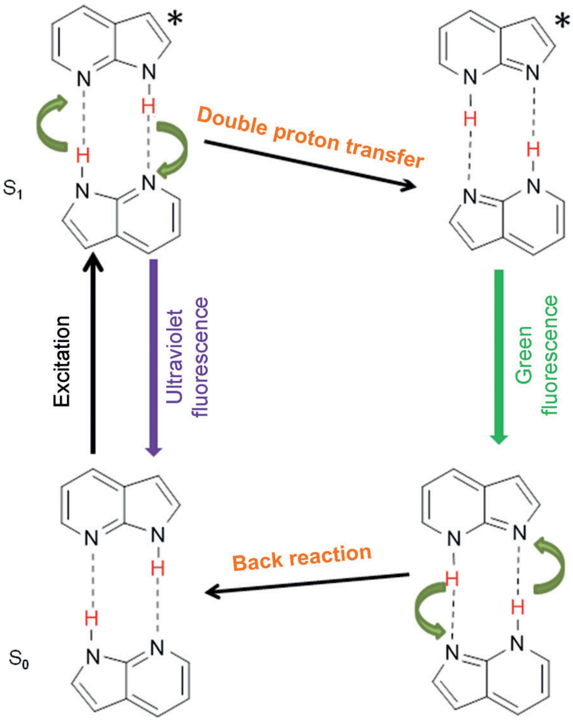

Figure 8. Excited-state double proton transfer in the 7AI dimer, resulting in dual fluorescence.

It was also discovered that not only double but also triple emission is possible in systems exhibiting ESIPT behavior. One emission comes from the normal locally excited state emission $S_1(\mathrm{LE})\rightarrow S_0$; another from the proton-transfer tautomer emission $S'_1(\mathrm{PT})\rightarrow S'_0(\mathrm{PT})$; and the third from the twisted intramolecular charge-transfer emission $S''_1(\mathrm{TICT})\rightarrow S_0$. A comparative picosecond spectroscopic study of the competitive triple fluorescence of aminosalicylates and benzanilides[42] demonstrated this effect[56] and its modulation by polarization of the dielectric medium.[57] Competition between dipolar relaxation and double proton transfer in the electronic spectroscopy of pyrroloquinolines was also demonstrated.[58]

Kasha was the first to apply the mechanism of intramolecular proton transfer to constructing dye lasers. This possibility was proposed theoretically by Khan and Kasha in 1983,[59] and the experimental demonstration of 3HF as an ESIPT laser dye was undertaken in 1984 by Chou, Kasha et al.[60] The first torsional-laser molecular dyes were also reported by Kasha et al. for phenylimidazoles[61] and phenyloxazoles,[62] some of them possessing amplified spontaneous emissions with peaks at short UV wavelengths.

How Did Michael Kasha Conduct His Research?

Surprisingly, Kasha's deep interest in a broad range of diverse phenomena was not associated with thoroughly checking the literature. Most of the information that he obtained came from his discussions with other scientists, and this allowed him to keep up to date on a range of topics. Kasha was open to discussion on various subjects, both related and unrelated to science. He always talked and questioned quite a lot, but all that he said or wrote was meaningful. In every congress, he usually gave a keynote speech and asked the other speakers many questions. Discussions about science always continued at lunches and dinners. When analyzing his impressive publication list, one may note that it is not as long as those of some other scientists of his age. One of his maxims was to report the most original work, and he did not worry much about systematic studies. He always thought that although at the beginning of his career his publication frequency was lower than at the end, those first papers were the most important and influential ones. He insisted that publishing a lot of papers was not necessarily a sign of excellence.

Another key point in Kasha's research was serendipity—with special humor, he named one of his workrooms the "Serendipity Room". Serendipity may be thought of as a "happy accident", "pleasant surprise", or even a "fortunate mistake". Specifically, it is the accident of finding something good or useful while not specifically searching for it. Kasha's research was marked by such serendipity, and also by spontaneity and curiosity. Learning had little meaning for Kasha unless it produced a sustained and substantial influence on the way people think, act, and feel.

Michael Kasha, the Educator

Those who had the privilege of being one of Kasha's students or co-workers always remark on the special freedom they had in doing their studies. He knew well how to shape a solid research group without putting any pressure on people, by giving his students the liberty to do research on their own or by collaborating with others. He felt a profound respect for his students and did not blame them for any of the difficulties they faced. Not every one of his colleagues accepted that, and not every one of his students could benefit from such encouragement to work on their own initiative; some even complained about the lack of attention, but they would all later realize the benefits. He enjoyed doing science, he enjoyed teaching students, and his excitement for learning the unknown infected everybody around him and was their strongest motivation for learning and research.

The fact that Kasha was an outstanding lecturer and a caring supervisor of his students and co-workers is manifested by the list of those who studied and worked with him. He mentored 33 PhD and 5 masters students in chemistry and biophysics. Many of the graduate students and postdoctoral research associates in his group have become recognized scientists. Recollecting the experience of working and studying with Michael Kasha, Mostafa El-Sayed, one of his graduate students, wrote "He was exciting and he created an atmosphere in his group which encouraged everyone [to] always [talk] with each other about research. We had beer and orbital theory seminars at Mike's house. This time taught me the importance of having peers in your research … I always liked Mike's very intuitive perspective on a phenomenon. He taught me the importance of looking for the big picture."[63] To all of us, he was incredible at taking the most complex problems and simplifying them to their essence. We may have lost him, but his influence continues.

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