

Vincenzo Balzani

Dipartimento di Chimica "G. Ciamician - Università di Bologna - Bologna - Italy

Franco Scandola

Dipartimento di Chimica - Università di Ferrara - Ferrara - Italy

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The interaction of light with matter is the most important natural phenomenon and the basis for a wealth of technological applications. In this and in two following articles that will appear in forthcoming issues, an account of photochemistry as a natural phenomenon and as a branch of modern science will be presented. In this first article, a few historical notations are reported and it is then shown that electronically excited states, obtained when a photon of suitable energy is absorbed by a molecule, are new chemical species which exhibit their own specific structure and reactivity. It is also shown that the interaction of light with matter can be used for energy conversion and information processing, two themes that will be elaborated in detail in the following articles.

And God said: "Let there be light!";
and there was light.
And God saw that light was good.
(Genesis, 1, 3-4)

1. INTRODUCTION

The interaction of light with matter is the most important natural phenomenon. It is responsible for the origin and evolution of life, the maintenance of living organisms, the deposits of coal, oil and natural gas, the possibility to map the environment (vision), and a number of other natural processes occurring in human beings, animals, plants, atmosphere, sea, and soil.

The interaction of light with matter became the object of scientific investigation about one century ago. In the last decades the development of this branch of science (named **photochemistry**) has resulted in many technological achievements (see Inset 1) which find extensive application and have a strong impact on everyday life of most people, especially in industrialized countries.

In this and in two following articles that will appear in forthcoming issues of this journal we will try to present an account of photochemistry as a natural phenomenon and as a branch of modern science. In the second and third articles we will particularly deal with the exploitation, in nature and technology, of the dual aspect of the photon: quantum of energy and bit of information.

2. HISTORICAL NOTATIONS

As a natural phenomenon, photochemistry is as old as the world. As a branch of science, however, photochemistry is quite young. We only need to go back less than one century to find the early pioneers of photochemistry. Among them, an outstanding role was played by Giacomo Ciamician, professor of chemistry at the University of Bologna from 1889 to 1921^{1,2}.

To perform a photochemical experiment one obviously needs a light source. At Ciamician's time there were neither lasers

Inset 1

Practical applications of Photochemistry	
Photochemistry is nowadays applied in a great variety of fields of technological value. e. g.:	
<i>Atmospheric chemistry</i>	modeling of troposphere, stratospheric ozone depletion, photochemical smog control
<i>Environment</i>	mineralization of organic pollutants, water purification
<i>Immunology</i>	fluoro- and chemiluminescence-detectable immunoassays
<i>Isotope enrichment</i>	multiphoton dissociation, photoionization
<i>Microelectronics Lasers</i>	photoresists, microlithography cw or pulsed, from UV to IR, for applications in physics, chemistry, medicine, engineering, etc.
<i>Materials science</i>	photochromic materials
<i>Medicine</i>	photodynamic therapy or tumors, phototherapy of jaundice
<i>Molecular biology</i>	DNA intercalation, cleavage, conformation probing
<i>Optics</i>	nonlinear optics, electro-optic materials, second-harmonic generation, optical waveguides
<i>Organic synthesis fine chemicals</i>	vitamins, antibiotics, steroids, prostaglandins, fragrances
<i>Organic synthesis large scale</i>	photohalogenations, photooxidations, caprolactam
<i>Photoimaging</i>	photography, xerography
<i>Photocatalysis</i>	heterogeneous photooxygenation, photohydrogenation, homogeneous photooxidations
<i>Polymer chemistry</i>	photopolymerization, photocrosslinking, photodegradation, stereolithography
<i>Solar energy</i>	photovoltaic devices, photogeneration of fuels, energy storage

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nor xenon or mercury lamps and the light from the electric bulbs was too faint and too red to be effective for photochemical excitation. The only light source available for photochemical experiments, therefore, was the sun and this was the reason why Ciamician's laboratory was located on the roof of the Institute, as documented by the well known picture displayed in fig. 1. At that time the possibility to perform photochemical experiments was strictly dependent on the weather conditions. This, of course, was not very convenient for planning experiments and obtaining reproducible results, as it clearly appears from a series of papers of the French scientist G. Lemoine³. He complained of the bad climate of Paris

"J'ai dû me contenter de la lumière solaire; comme sous le climat de Paris les belles journées sont très rares, ces recherches ont été très laborieuses et très longues"

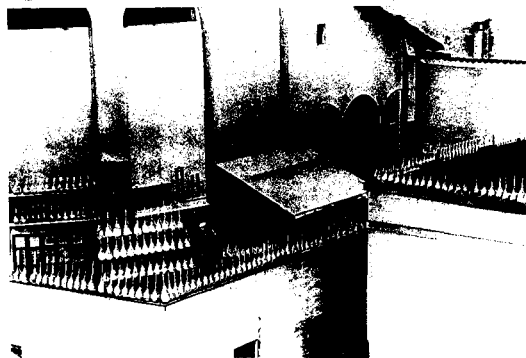


Figure 1. A photochemical laboratory at the beginning of this century: Giacomo Ciamician surveying dozens of flasks exposed to sunlight on the roof of the Chemistry Institute at the University of Bologna.

and eventually he moved to the Swiss Alps to find more intense (and ultraviolet) light. Among the experimental conditions carefully reported in Lemoine's paper, the most important (and determinant) one is the notation of the weather conditions, as shown from the table reproduced in fig. 2.

Although sunlight is not much suitable to obtain reproducible and quantitative data in scientific photochemical experiments, photochemistry is the most convenient way to convert the abundant and inexhaustible resource of solar energy

into forms of energy useful for the progress of mankind (e.g., electricity and fuels). This idea was clearly expressed by Giacomo Ciamician (University of Bologna) in a famous lecture entitled "The Photochemistry of the Future" delivered in New York at the VIII International Congress of Applied Chemistry (1912)⁴. At the time of the apex of coal technology, Ciamician pictured a future society based on the sun as direct energy source:

"So far human civilization has made use almost exclusively of fossil solar energy. Would it not be advantageous to make better use of radiant energy?"

Ciamician also realized that a civilization based on solar energy could re-equilibrate the economic gap, already existing at that time, between northern and southern regions of the world:

"Solar energy is not evenly distributed over the surface of the earth. There are privileged regions, and others that are less favored by the climate. The former ones would be the prosperous ones if we should become able to utilize the energy of the sun. The tropical countries would be conquered by civilization which would in this manner return to its birth-place."

The final sentence of that paper presents a concept quite meaningful even today (we should only add oil and nuclear energy to coal):

"If our black and nervous civilization, based on coal, shall be followed by a quieter civilization based on the utilization of solar energy, that will not be harmful to the progress and to human happiness."

Ciamician realized that an important difference between natural and artificial chemical synthesis was the much milder conditions of natural synthetic processes, due to the ability of plants to make use of solar light which is a form of energy much more effective and "noble" than heat. As a consequence, he decided to carry out systematic investigations to reproduce natural photochemical reactions "in vitro". He also realized the wide scope of photochemistry and the great importance for the future of humanity of a correct exploitation of a fundamental energy resource: solar energy. Ciamician ideas had a large impact on the chemical community and stimulated many systematic photochemical studies especially in the field of organic chemistry^{1,2}. In the same period, most eminent scientists like Einstein and Planck elaborated the quantum model of light which, a few years later, allowed photochemistry

Résultats des expériences pour les tubes circulaires avec la lumière blanche. -- Elles ont été faites principalement en mesurant le gaz dégagé avec des tubes de 14^{mm} placés verticalement.

Mélanges de liquides actifs.				Dates des expériences.		ε.
Normaux.	$\frac{1}{2}$ N.	$\frac{1}{4}$ N.	$\frac{1}{8}$ N.			
Expériences : rapports entre les fractions de décomposition $\left(\frac{Y}{P}\right)$ pour un même temps dans des tubes circulaires de 14 ^{mm} de diamètre, placés verticalement.						
	1	»	2,16	4,46	23 sept. 1883, de 11 ^h 02 à 11 ^h 26 : très beau temps.	1,3
	1	»	1,63?	»	27 mai 1884, de 10 ^h 54 à 11 ^h 52 : ciel magnifique.	2,1
	1	»	1,44?	»	6 août 1884, de 2 ^h 55 à 3 ^h 44 : très beau temps.	1,3
	1	»	1,67?	»	8 août 1884, de 3 ^h 22 à 4 ^h : beau temps.	1,25
	1	»	1,65	»	22 octobre 1884, de 11 ^h 25 à 12 ^h 30 : beau temps.	1,2
	1	»	1,47	»	23 octobre 1884, de 10 ^h 20 à 10 ^h 55 : très beau temps.	1,1
	1	»	1,56	»	24 octobre 1884, de 11 ^h 45 à 12 ^h 38 : très beau temps.	1,1
	1	»	1,87	»	25 octobre 1884, de 1 ^h 15 à 2 ^h 23 : très beau temps.	1,1
Déterminations d'après la mesure du gaz dégagé.....	1	»	1,66	»	4 juin 1885, de 3 ^h 35 à 4 ^h 30 : beau ciel.	1,2
	1	»	1,77	»	11 juin 1885, de 2 ^h 07 à 3 ^h 17 : ciel magnifique.	1,55
	1	»	1,54	»	24 juin 1885, de 2 ^h 43 à 3 ^h 08 : ciel magnifique.	1,5
	1	»	1,60	»	25 juin 1885, de 2 ^h 25 à 3 ^h 16.	1,5
	1	»	2,32	»	24 juin 1886, de 3 ^h 42 à 4 ^h 26 : soleil assez pur.	1,25
	1	»	1,96	»	21 août 1886, de 1 ^h 44 à 2 ^h 16 : soleil assez pur.	1,4
	1	»	1,90	»	21 août 1886, de 4 ^h 25 à 5 ^h .	1,1
	1	»	2,04	»	28 août 1886, de 12 ^h 16 à 12 ^h 58 : beau temps.	1,5
1	»	2,04	»	5 août 1887, de 11 ^h 55 à 12 ^h 51.	1,8	

Figure 2. Old days photochemistry: a table taken from a paper of G. Lemoine³ reporting the results obtained upon irradiation with sunlight of ferric oxalate solutions.

to emerge from its empirical stage to answer the question "how has it occurred?" that Ciamician could not tackle.

3. PHOTOCHEMISTRY: A NEW DIMENSION OF CHEMISTRY

The fundamental concept introduced into photochemistry by modern physics was that light absorption corresponds to the "capture" of a photon ($h\nu$) by a ground-state molecule (A) to give an "excited state" $*A$ (eq 1).



With this concept in mind, Stark (1908-12) and Einstein (1912-13) proposed that in a photochemical process there should be a 1:1 equivalence between the number of molecules decomposed and the number of quanta absorbed. On this hypothesis, the quantum yield of a photochemical reaction obeying the "one molecule per photon" law should be unity. Then Bodenstein realized that when the primary products of a photo-process are radical species, they can initiate secondary thermal reactions which can lead to quantum yield higher than unity. In that period mercury lamps, equipped with monochromators or light filters, became the usual source for light excitation.

The model of the atom proposed by Bohr (1916) and the development of spectroscopic techniques set the grounds for a sound definition of the concept of *electronically excited state*, which since then plays a central role in photochemistry. It became clear that whereas the usual (thermal) reactions involve the electronic ground state of molecules, photochemical reactions originate from electronically excited states which can be reached by light absorption (Fig. 3). And *photochemistry* began to be defined as *the branch of science that deals with the processes originating from electronically excited states*.

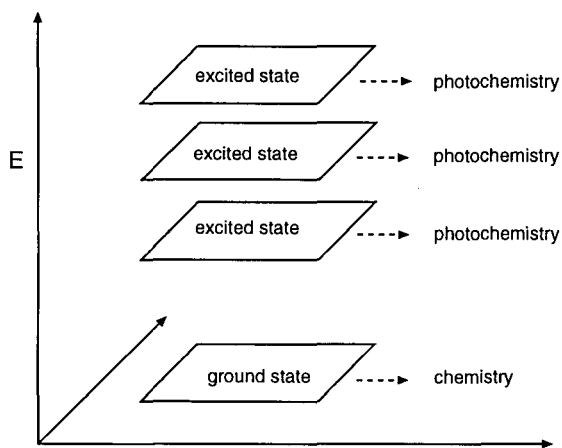


Figure 3. The usual (thermal) reactions involve the ground state of molecules, whereas the photochemical reactions involve electronically excited states. Photochemistry can thus be viewed as a new dimension of chemistry.

3.1 Excited states: basic properties and decay processes

In modern photochemistry⁵, the excited states of a molecule are described in terms of molecular orbitals (MOs). The MOs form the basis for the *electronic configurations*, i.e., the product wavefunction indicating which molecular orbitals are occupied in each state. Formaldehyde is a simple organic molecule which can be used to exemplify the procedure to construct states from electronic configurations. The MO diagram of formaldehyde is schematically shown in fig. 4. It consists of three low-lying σ -bonding orbitals, a π -bonding orbital of the CO group, a nonbonding atomic orbital of oxygen, a π -antibonding

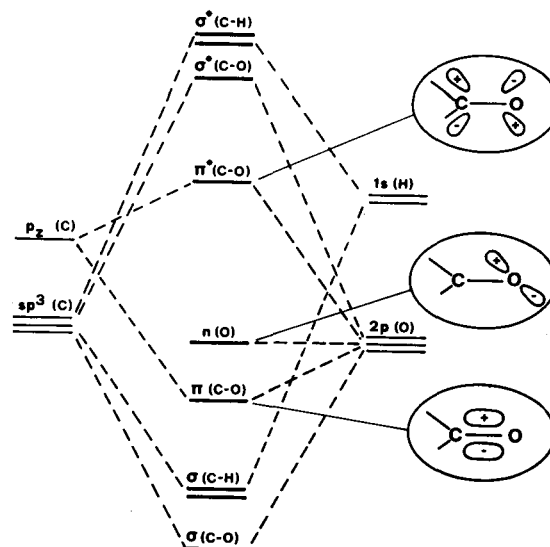


Figure 4. Schematic MO diagram for formaldehyde.

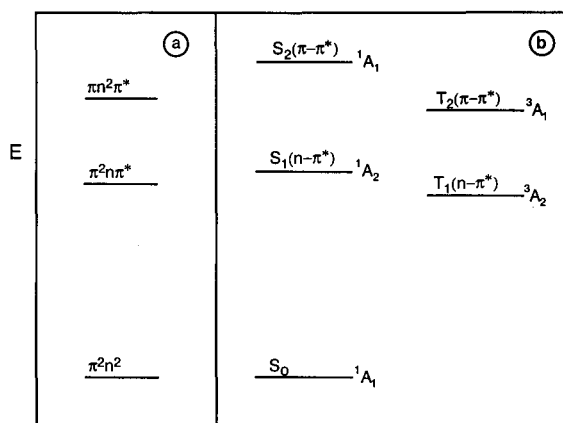


Figure 5. Schematic configuration (a) and state (b) diagrams for formaldehyde.

orbital of the CO group, and three high-energy σ -antibonding orbitals. The lowest-energy electronic configuration (neglecting the filled σ -bonding orbitals) is $\pi^2 n^2$. Higher-energy configurations can be obtained from the lowest one by promoting electrons to antibonding orbitals: $\pi^2 n \pi^*$, $\pi n^2 \pi^*$, and so on. In a very poor description, the energy of each electronic configuration could be considered as the sum of the energies of the occupied MOs (Fig. 5a). To obtain a more realistic description of the true energy states of a molecule, however, *spin* and *interelectronic repulsions* must be added to the picture. These two closely interlocked effects lead to the splitting of each excited configuration into two states: an upper "singlet" state (with paired electron spins and larger interelectronic repulsions) and a lower "triplet" state (with parallel electron spins and smaller interelectronic repulsions) (Fig. 5b). State energy diagrams such as that of fig. 5b (commonly called Jablonski diagrams) are used for the description of the primary photoprocesses that take place following excitation of a molecule. The situation [singlet ground state, pairs of singlet (higher) and triplet (lower) states for each excited configuration] is quite general, being typical of most organic molecules.

Because of their different electronic distribution, excited states can exhibit chemical and physical properties quite different from those exhibited by the correspondent ground state molecule. A wealth of experimental and theoretical evidences demonstrate that this is indeed the case. A few examples are shown in table 1. In general it can be said that an

Table 1. Comparison between some properties of ground and excited state for a few selected molecules

	ground state	excited state
HCN^a		
H-C bond distance	1.06 Å	1.14 Å
C-N bond distance	1.16 Å	1.30 Å
bond angle	180°	125°
Formaldehyde^b		
geometry	planar	pyramidal
magnetism	diamagnetic	paramagnetic
dipole moment	2.3 D	1.3 D
C-O bond distance	1.22 Å	1.31 Å
4-Amino,4'-nitro-<i>p</i>-diphenyl^c		
dipole moment	5 D	16 D
Phenol^c		
pK _a	10	4
Ru(bpy)₃²⁺		
reduction potential	-1.28 V	+0.84 V
1-nitro-3,4-dimethoxybenzene^c		
nucleophilic attack (OH ⁻)	4 position	3 position
<i>trans</i>-Cr(NH₃)₄Cl₂⁺		
ligand substitution product (H ₂ O)	<i>trans</i> -Cr(NH ₃) ₄ (H ₂ O)Cl ₂ ⁺	<i>cis</i> -Cr(NH ₃) ₃ (H ₂ O)Cl ₂ ⁺

^a ¹A" excited state

^b Lowest energy, spin-forbidden excited state

^c Lowest energy, spin-allowed excited state

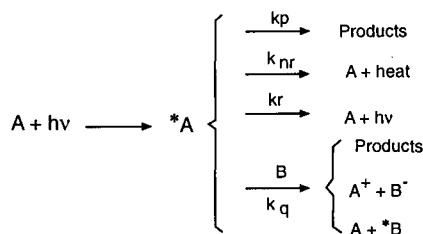


Figure 6. Competition between unimolecular and bimolecular deactivation processes of an excited state.

electronically excited state is a new chemical species compared to the ground state molecule. Which means that photochemistry is a new dimension of chemistry (Fig. 3).

Besides the above-mentioned peculiarities, electronically excited states have another fundamental difference with respect to the ground state: they are created by an external perturbation (light absorption) and have necessarily a transient character. As a matter of fact, a variety of uni- or bimolecular, chemical or physical processes are available to deactivate an electronically excited state (Fig. 6). Thus, whether an excited state will survive long enough to manifest itself, and which of its properties will show up, depend dramatically on the competition between the various deactivation paths and, ultimately, on their kinetics. In the absence of bimolecular processes, the excited state will decay with an overall first-order kinetics with a lifetime $\tau(*A)$ given by

$$\tau(*A) = \frac{I}{k_r + k_{nr} + k_p} = \frac{I}{\sum_j k_j} \quad (2)$$

The timescales of excited-state phenomena are briefly discussed in Inset 2. For each process of the *A excited state (Fig. 6), an efficiency $\eta_i(*A)$ can be defined as

$$\eta_i(*A) = \frac{k_i}{\sum_j k_j} = k_i \tau(*A) \quad (3)$$

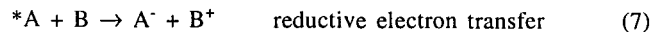
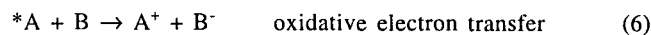
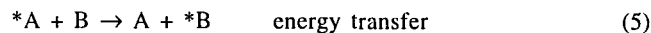
The quantum yield of a given process originating from *A is

defined as the ratio between the number of molecules undergoing the process per unit time and the number of photons absorbed per unit time. If the *A excited state is directly populated by light absorption, the quantum yield coincides with the efficiency of the process. If, on the other hand, the *A excited state is indirectly populated following one or more nonradiative steps from other excited states, the quantum yield is given by

$$\Phi = \Pi_n \eta_n \eta_i(*A) \quad (4)$$

where η_n represents the efficiency of the steps involved in the population of *A.

In addition to the unimolecular processes considered above, an excited state *A can also decay via bimolecular processes, following interaction with some other species, B (Fig. 6). This may happen when the lifetime of the excited state (eq 2) is long enough to allow encounters with B (in practice, lifetimes at least of the order of nanoseconds are required for such processes to be feasible). Of particular relevance to the problems and applications that will be discussed in Parts 2 and 3 of this series is the capability of an excited state to transfer energy⁶ and to transfer/receive an electron⁷ to/from another species:



Energy transfer, of course, is an exclusive process of excited states, whereas electron transfer, either reductive or oxidative, can also be given by ground state molecules. An excited state, however, is much more prone to undergo electron transfer processes than the corresponding ground state, because its excess energy can be used as free energy in the redox process. It can be shown that, to a first approximation, the potentials for redox couples involving the excited state can be obtained from the potentials of the ground-state couples and the one-electron potential E^{0-0} (V) corresponding to the zero-zero spectroscopic energy of the excited state⁸:

$$E(A^+/*A) = E(A^+/A) - E^{0-0}(V) \quad (8)$$

Inset 2

The timescale of photochemical techniques

On the time scale of conventional kinetics, deactivation of electronically excited states is a very fast process. Typical rate constant values for radiationless decay (Fig 6) may range from s^{-1} (e. g., for lowest triplet states of organic molecules) to $10^9 s^{-1}$ (e.g., for lowest singlet states of organic molecule) to $10^{12} s^{-1}$ (for upper excited states). Thus, any photochemical or photophysical process of interest (emission, chemical reaction, bimolecular processes), to be efficient, must also occur in a very short timescale. This is why direct observation of excited states and of their processes requires the use of fast techniques based on pulsed lasers as excitation light sources. With such techniques, measurements in the *microsecond* (10^{-6} s) *nanosecond* (10^{-9} s) and *picosecond* (10^{-12} s) timescales are now commonly performed in many photochemical laboratories. Extension into the *femtosecond* (10^{-15} s) time domain is now the frontier of fast time-resolved methods in photochemistry. This is also likely to be the ultimate limit of the rush towards shorter times: from a practical viewpoint, one is reaching the timescale of the fastest chemical acts (nuclear motion); on the theoretical side, limitations due to the uncertainty principle begin to show up (a precision of 1 fs implies an uncertainty in energy comparable to the energy of chemical bonds).

With fast and ultra-fast lasers as excitation sources, various spectroscopic techniques (including luminescence, UV/vis and IR absorption, and resonance Raman) can be used to study the excited states or other transient species formed. As a consequence of these spectacular advances in instrumentation, the aspect of the photochemical laboratory (Fig A) has changed quite substantially since Ciamician's times (Fig. 1)

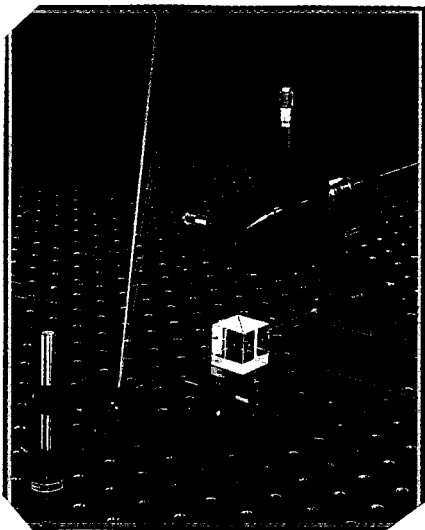


Fig. A Typical aspect of a modern photochemical laboratory, characterized by the use of lasers as excitation sources

$$E(*A/A^{\cdot}) = E(A/A^{\cdot}) + E^{0,0}(V) \quad (9)$$

It should be emphasized that, as shown quantitatively by eqs 8 and 9, an excited state is *both* a stronger reductant *and* a stronger oxidant than the ground state from which it derives. For example (Fig. 7) $Ru(bpy)_3^{2+}$ (bpy = 2,2'-bipyridine) in its ground state is difficult to reduce and to oxidize, so that is neither a good oxidant nor a good reductant; its lowest excited state, with a

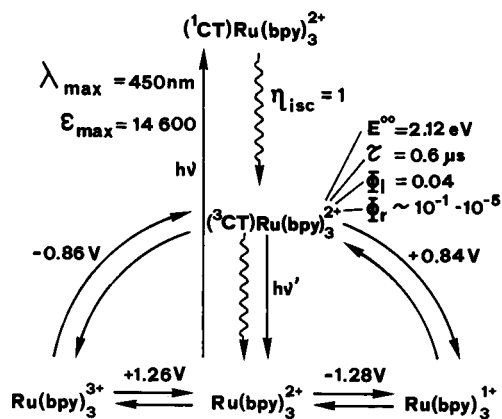


Figure 7. Schematic representation of some ground and excited state properties of $Ru(bpy)_3^{2+}$. 1CT and 3CT are the spin-allowed and spin-forbidden metal-to-ligand charge-transfer excited states. The quantities shown are: intersystem crossing efficiency (η_{isc}); energy ($E^{0,0}$) and lifetime (τ) of the 3CT state; luminescence quantum yield (Φ_l); quantum yield for ligand detachment (Φ_r). The reduction potentials of couples involving the ground and 3CT excited state are also indicated. All the data refer to aqueous solutions at room temperature, except Φ_r which refers to a variety of experimental conditions. The potentials are vs NHE.

spectroscopic energy of 2.12 eV, is both a good oxidant and a good reductant⁸, as will be seen in more detail later on.

4. RELEVANCE OF PHOTOCHEMICAL PROCESSES IN NATURE AND TECHNOLOGY

Light is made of photons, and photons are at the same time *energy quanta* and *information bits*. All the natural phenomena related to the interaction between light and matter, and the great number of applications of photochemistry in science and technology (see Inset 1), can ultimately be traced back to these two aspects of light. In particular, sunlight is exploited by living organisms as energy in photosynthetic processes and as information in visual processes (Fig. 8, top). The most important aim of photochemistry is the design and construction of artificial energy-conversion and information-processing devices capable to feed and control the great variety of machines that sustain our civilization (Fig. 8, bottom). These topics will be treated in some detail in the following two articles of this series. Here we will only anticipate some fundamental concepts related to these topics.

4.1 Photochemical conversion of solar energy

In the poetical words of W. Ostwald¹¹

"Life is a water mill: the effect produced by the falling water is achieved by the rays of the sun. Without the sun the wheel of life cannot be kept going. But we have to investigate more closely which circumstances and laws of Nature bring about this remarkable transformation of the sunrays into food ..."

In the past few decades such "circumstances and laws" have been at least in part elucidated, and Ciamician's dream⁴ to fix solar energy through suitable artificial photochemical reactions may become reality^{9,10}. A more detailed account of this problem will be given in Part 2 of this series. For the moment we can use a simple example, based on an oxidation-reduction reaction, to illustrate how light can be transformed by photochemical processes into chemical energy. Consider the reaction in aqueous solution between $Ru(bpy)_3^{2+}$ and Fe^{3+} to give $Ru(bpy)_3^{3+}$ and Fe^{2+}

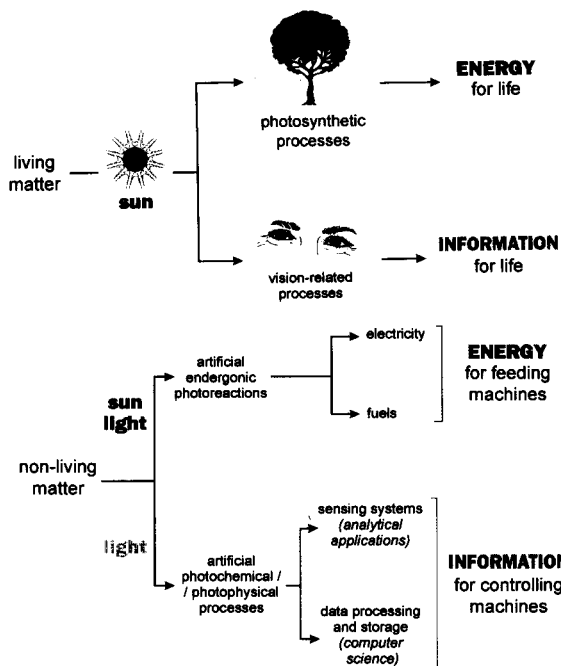
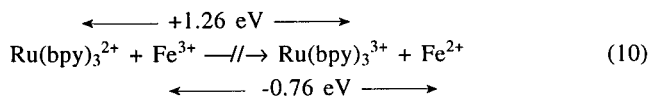
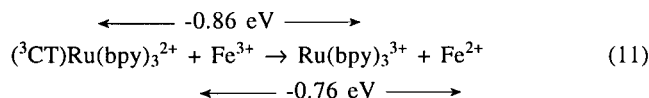


Figure 8. (top) In nature photons are exploited by living organisms as energy in photosynthetic processes and as information in visual processes. (bottom) An important aim of artificial photochemistry is the design and construction of artificial energy-conversion and information-processing devices.



This reaction does not occur in the dark because it would imply an increase in free energy, as $\text{Ru}(\text{bpy})_3^{3+}$ is a stronger oxidant than Fe^{3+} . If the solution is exposed to visible light, $\text{Ru}(\text{bpy})_3^{2+}$ absorbs a photon and is promoted from the electronic ground state to high energy electronic excited states which rapidly relax to the lowest excited state, $(^3\text{CT})\text{Ru}(\text{bpy})_3^{2+}$ (Fig. 7). Such an excited state, as we have seen above, is a much better reductant than the ground state, and it is also a better reductant than Fe^{2+} . Since $(^3\text{CT})\text{Ru}(\text{bpy})_3^{2+}$ lives long enough to encounter Fe^{3+} ions in solution, it can reduce Fe^{3+} to Fe^{2+} :



As schematically shown in fig. 9, this amounts to convert light into chemical (redox) energy. Such a system, however, is useless because the products of reaction 11, as soon as they are formed, react to give back $\text{Ru}(\text{bpy})_3^{2+}$ and Fe^{3+} . In other words, in the above system sunlight is converted into chemical energy that cannot be stored. Artificial energy conversion systems, in order to be useful, should either produce kinetically stable forms of redox energy (e.g., fuels), or take advantage of a transiently generated redox energy to produce electric power.

4.2 Use of light for information purposes.

Interaction of light with matter can be exploited to modify the properties of matter, e.g., by transforming a substance into a different one. Exploitation of photons for information purposes can be performed by two different routes (Fig. 10)^{9,10}.

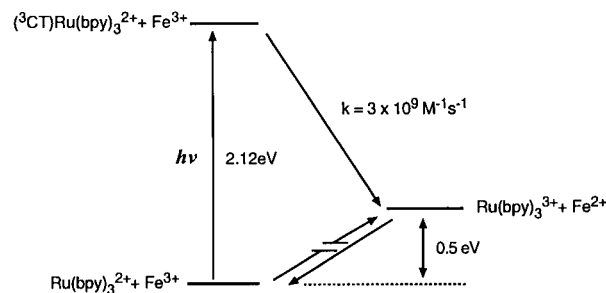


Figure 9. Schematic representation of the conversion of light energy into chemical energy in the $\text{Ru}(\text{bpy})_3^{2+}\text{-Fe}^{3+}$ system.

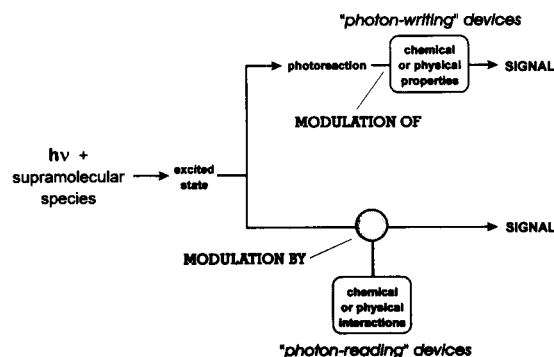


Figure 10. Photochemical reactions can be used to obtain information either "writing" on matter or "reading" the state of matter.

The first one involves the occurrence of a photoreaction. This amounts to "write" on matter with light. The best known example is, of course, the photographic process, which was empirically discovered much before the birth of photochemistry as a science. In the last few decades, the techniques to "write" on matter by light, and even to "erase" by light previously written pieces of information, have been strongly developed^{12,13}. Photochromic substances¹⁴, i.e., compounds which may exist as two, differently colored isomers that can be interconverted upon light excitation (eq 12), had already



called the attention of Giacomo Ciamician as a social communication means⁴:

"Photochromic substances might be used very effectively.... The dress of a lady, so prepared, would change its color according to the intensity of light: the last word of fashion for the future".

Ciamician, however, could not predict the use of binary logic intrinsic to photochromic substances for processing and storing information bits, nor the use of lasers, with their monochromatic, intense, and collimated beams, as writing devices¹⁵.

Besides "writing" on matter, light can also be used to "read" matter, i.e., to reveal modifications performed by external inputs on chemical substances (Fig. 10). For example, the occurrence of a chemical reaction (acid/base, redox, etc.) that changes the absorption or emission spectrum of a substrate can be easily detected. Such processes can again be used for information processing and storage, as we will see in more detail in Part 3.

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