Photochromic flavylium compounds as multistate/multifunction molecular-level systems

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Synthetic flavylium compounds can exist in several forms (*multistate*) that can be interconverted by more than one type of external stimulus (*multifunctional*). The intricate network of their reactions, when examined from the view point of 'molecular-level devices', reveals very interesting properties.

Introduction

Great effort is currently being devoted to the design of molecular-level switching devices and, more generally, to the chemistry of signal generation, transfer, conversion, storage, and detection (semiochemistry).[1] By reducing the switching elements to molecular size, the memory density of computers could be increased by several orders of magnitude and the power input decreased very significantly.[2] Apart from future applications for information processing at the molecular level,[3] the study of compounds capable of existing in different forms that can be interconverted by external stimuli is a topic of great fundamental interest.[1–9] Molecules that can exist in two forms which are interconvertible by an external input are rather common. Typical examples of such bistable systems are the so-called photochromic compounds, where the input causing the switching between the two species is light.[10] Systems capable of existing in more than two forms (*multistate*) that can be interconverted by more than one type of external stimulus (*multifunctional*) are less common.[11,12] Such multistate/multifunctional systems can behave as complex logic devices and can therefore play the role of models for an initial understanding of the chemical basis of important biological processes.

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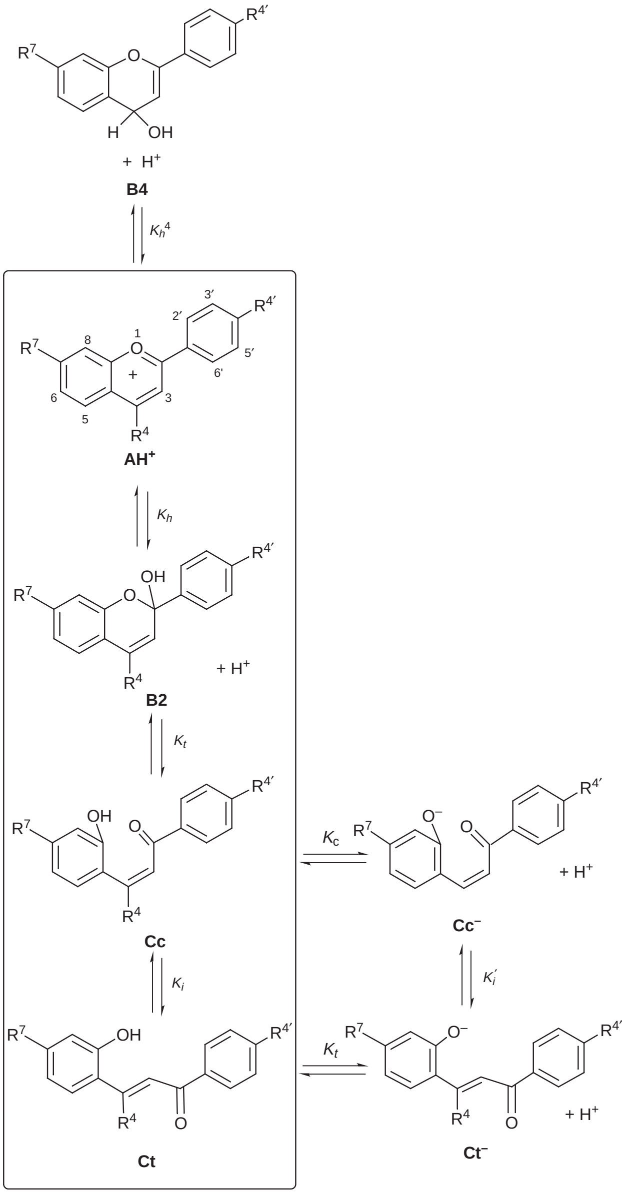
Like anthocyanins,[13] which are one of the most important sources of colour in flowers and fruits, synthetic flavylium salts in aqueous solutions undergo various structural transformations[14–17] that can be driven by pH changes and, particularly in the flavylium salts, also by light excitation. Such transformations are often accompanied by quite dramatic colour changes or colour disappearance. In the last few years we have investigated in a systematic way the thermal and photochemical reactions of several synthetic flavylium salts.[18–23] The main purpose of our studies has been to emphasize the multistate/multifunctional character of the chemistry of these compounds and, more generally, to show that examination of complex chemical systems from the view points of 'molecular-level devices' and 'molecular level logic functions' may reveal very interesting aspects and may be useful to introduce new concepts in the field of chemical research.

Nature of the species involved

The basic scheme for the discussion of the structural transformations of flavylium-type compounds is that shown in Scheme 1.[14–17] As we will see below, other forms may also be involved, depending on the nature of the substituents in the 4-, 7-, and 4′-positions. The flavylium cation **AH^+**, which is the stable form in strongly acid solution, can be easily prepared by acid condensation of salicylaldehyde and acetophenone derivatives, as well as by other routes.[24] In moderately acidic or neutral solution, the thermodynamically stable form is the neutral *trans*-2-hydroxychalcone species **Ct**, which is formed from **AH^+** through the two intermediate compounds **B2** and **Cc**. **B2** is a hemiacetal species, obtained by hydration of the flavilyium cation, and **Cc** is a *cis*-2-hydroxychalcone, formed from the hemiacetal **B2** through a tautomeric process. The interesting feature of these systems is that the **AH^+** and **B2** forms can be reversibly interconverted by pH changes,[14–17] whereas **Cc** and **Ct** can be interconverted by photoexcitation.[18–23,25–28] Since the **B2** and **Cc** forms are in tautomeric equilibrium, it follows that pH and light stimulations can be used to cause interconversion of the four fundamental forms (Scheme 1). Furthermore, the **AH^+** form exhibits acid properties not only in the 2-, but also in the 4-position, to give the **B4** basic species. In their turn, **Cc** and **Ct** can undergo deprotonation to give the respective **Cc^-** and **Ct^-** monoanions which, being *cis*/*trans* isomers, can in principle be interconverted by light excitation. As we will see later, depending on the nature of the substituents, other acid/base equilibria and *cis*/*trans* couples may be present. It is therefore clear that in these systems pH changes coupled with light excitation may cause very intricate series of chemical reactions, with dramatic changes in the absorption spectra (*i.e.* in the colour of the system). A further interesting aspect is that some of the species exhibit fluorescence; this is not only another analytical 'handle' to control the behaviour of the system, but also a very interesting signal for the purpose of information processing.

Several works concerning the thermodynamic as well as the kinetic aspects of the thermal reactions of flavylium-type compounds have long since been reported in literature,[13–17] whereas the photochemical and photophysical aspects have been examined more recently.[14–23,28] As we shall see below, pH jump, temperature jump, and flash photolysis experiments allow the measurement of the rate constants of some of the reactions involved, and steady state titration experiments (by using UV–VIS and NMR techniques) allow the measurement of equilibrium constants. In order to illustrate the complex reaction network of these systems, we will now focus on the behaviour of the 4′-methoxyflavylium ion[19] (Scheme 1; $R^4 = R^7 = H$, $R^{4'} = OCH_3$).



Scheme 1 Structural transformations of the flavylium-type compounds. Only the most important forms are shown.

Thermal reactions of the 4′-methoxyflavylium ion

A very careful spectral and kinetic investigation of the transformations undergone by the 4′-methoxyflavylium ion was originally performed by McClelland and Gedge.[16] By using the pH jump technique, they found that seven different species are involved, as transient or equilibrium compounds, depending on the experimental conditions (Scheme 1). The absorption spectra of the strongly colored 4′-methoxyflavylium ion **AH$^+$** (λ_{max} = 435 nm, ε = 42000 M^{-1} cm^{-1}), the colorless *trans*-4′-methoxychalcone **Ct** (λ_{max} = 350 nm, ε = 18000 M^{-1} cm^{-1}), and the **B2** and **Cc** mixture are shown in Fig. 1.

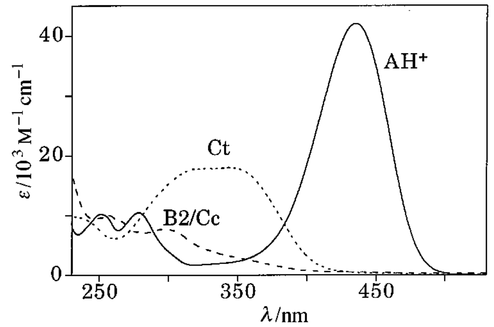


Fig. 1 Absorption spectra in aqueous solution at 25 °C of the 4′-methoxyflavylium compound: **AH$^+$** at pH 1.0, **Ct** at pH 4.0 and **B2**/**Cc** mixture at pH 7.0. Reprinted with permission from ref. 19.

The molar fraction distribution[16,27a] of the various species in aqueous solution at 25 °C as a function of pH, obtained from the equilibrium constants (*vide infra*), is shown in Fig. 2. The thermodynamically stable form in the pH range 2–8 is the *trans*-4′-methoxychalcone, **Ct**, which, at higher pH, is transformed into its anion, **Ct$^-$** (Fig. 2, solid lines). In strongly acidic solutions, **AH$^+$** becomes thermodynamically stable; however, **Ct** cannot be converted to **AH$^+$** because of the very large activation barrier which involves isomerization of **Ct** to the intermediate compound **Cc** (Scheme 1). Furthermore, a solution of **AH$^+$** is almost indefinitely stable at room temperature below pH 3, since under such conditions a very large kinetic barrier prevents conversion of **AH$^+$** to the thermodynamically stable **Ct** form *via* the hydrated (pseudobase) species **B2** and the **Cc** isomer (Scheme 1). At higher pH, however, **AH$^+$** is very reactive.[16] For example, starting from an aqueous solution of **AH$^+$** at 25 °C and pH 1, a pH jump to pH 4.29 leads within a few seconds to a pseudo-equilibrium consisting of 50% **AH$^+$**, 33.2% **B2**, 0.3% **B4**, and 16.5% **Cc** (Fig. 2, dashed lines). A much slower reaction follows (half-life 19.7 h), resulting in complete conversion to the thermodynamically stable form **Ct**.

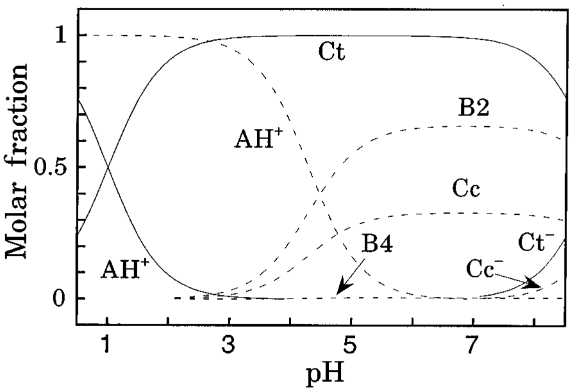


Fig. 2 Molar fraction distribution in aqueous solution at 25 °C as a function of pH for the 4′-methoxyflavylium compound. Solid lines refer to the species obtained at the thermodynamic equilibrium. Dashed lines refer to species obtained bringing **AH$^+$** solutions from pH 1 to higher pH values by the pH jump technique or by exciting **Ct** solutions by flashed light. Such species reach a pseudo-equilibrium on the second time scale and then undergo a very slow thermal reaction to **Ct**. Reprinted with permission from ref. 19.

At pH 8, **AH$^+$** reacts mainly with solvent water[16] (half-life 0.44 s) to produce 64% **B4**, 24% **B2**, and 12% **Cc**, the last two being in equilibrium with each other (half-life of the equilibration, 7×10^{-5} s). This is followed by another fast reaction (half-life 66 s) in which **B4**, a product of kinetic control of the initial neutralization of **AH$^+$**, is converted *via* **AH$^+$** to **B2** and **Cc**, yielding a pseudo-equilibrated mixture of 66.3% **B2**, 33.1% **Cc**, and 0.6% **B4** (Fig. 2, dashed lines). A much slower reaction (half-life 9.9 h) then occurs, resulting in complete conversion to **Ct**.

Photochemical behaviour of the 4′-methoxyflavylium ion

As described above, in the pH range 2–8 the colorless *trans*-4′-methoxychalcone **Ct** is the thermodynamically stable species and therefore it is the final product of the transformations of the strongly colored 4′-methoxyflavylium ion **AH**$^+$. Even at pH 1, when **AH**$^+$ is the thermally stable species, **Ct** can be kinetically stable because of the high energy barrier of its transformation to **Cc**. **Ct**, however, can be converted into **AH**$^+$ by a photochemical reaction.[19] As expected from the thermal behavior of the system, the photoreaction causes a transient or an almost permanent effect depending on temperature and pH of the irradiated solution.

Continuous irradiation[19]

Continuous irradiation of 2.3×10^{-5} M aqueous solutions of **Ct** at pH 1.0 with 365 nm light causes strong spectral changes, with five isosbestic points and formation of a very intense band in the visible region with maximum at 435 nm [Fig. 3(*a*)]. Analysis of the spectral changes shows that the photoreaction converts **Ct** into **AH**$^+$, without formation of sizeable amounts of other products. The quantum yield of the photoreaction is 0.04, independent of the presence of dioxygen in solution. At pH 1.0, no back reaction takes place and irradiation with 434 nm light, corresponding to the maximum of the absorption band of **AH**$^+$ (Fig. 1), does not cause any effect.

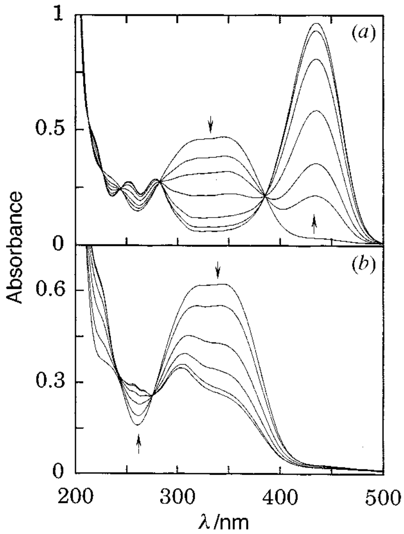


Fig. 3 Spectral changes caused by continuous irradiation of an aqueous solution of the **Ct** form of 4′-methoxyflavylium ion with 365 nm light: (*a*) pH 1.0, [**Ct**] = 2.5×10^{-5} M; the curves correspond to the following irradiation times: 0, 0.5, 1, 2, 4, 7 and 12 min. (*b*) pH 7.0, [**Ct**] = 3.2×10^{-5} M; the curves correspond to the following irradiation times: 0, 0.25, 1.5, 3, 6 and 10 min. Reprinted with permission from ref. 19.

When irradiation of **Ct** is carried out at pH 4.0, the quantum yield of the photoreaction leading from **Ct** to **AH**$^+$ does not change, but the expected thermal back reaction of **AH**$^+$ to **Ct** is observed. The rate of the back reaction increases with temperature (activation energy 93 kJ mol^{-1} at pH 4.0). Irradiation at pH 7.0 causes the spectral changes shown in Fig. 3(*b*). At this pH the disappearance of **Ct** does not cause any increase of absorbance in the visible spectral region, showing that **AH**$^+$ is not formed. Furthermore, the back reaction is very fast so that complete disappearance of **Ct** cannot be observed. This is in full agreement with the expectations based on the data shown in Fig. 2, which indicate that at pH 7.0 the pseudo-equilibrated mixture of products is constituted essentially by the open **Cc** and closed **B2** *cis* forms. Their absorption spectrum, as is always the case for aromatic derivatives of ethylene,[29] is less intense and slightly blue-shifted compared to the spectrum of the *trans* form (Fig. 1). Under such conditions, irradiation of the mixture with 313 nm light causes the reverse *cis* → *trans* photoisomerization reaction with an apparent quantum yield of *ca.* 0.5 (based on the total light absorbed by **Cc** and **B2**).

Interestingly, **Ct** and **AH**$^+$ exhibit intense fluorescence bands with $\lambda_{\max}$ at 430 and 530 nm, respectively.[19] The fluorescence lifetime is shorter than 1 ns in both cases. It is worth noting that the occurrence of the above-described thermal and photochemical reactions can also be followed by fluorescence measurements.

Pulsed irradiation[19]

Flash photolysis is a powerful technique for investigating the kinetics of conversion of the various forms of flavylium ions.[27*c*] Even using a simple flash-photolysis apparatus with a time resolution of *ca.* 0.2 s it is possible to obtain kinetic data that can complement and/or replace those obtainable by the pH jump technique.

Flash excitation[19] of a 6.0×10^{-5} M aqueous solutions of **Ct** at 25 °C and pH 3.0 or 7.0 causes a bleaching in the 300–400 nm region that can be assigned to the disappearance of **Ct**. At pH 3, a strong increase in absorbance in the 400–500 nm region is observed, as expected for the formation of **AH**$^+$. The absorbance *vs.* time traces show that **Ct** disappears within the time scale of the flash, but its disappearance does not lead directly to **AH**$^+$. One or more intermediate products are formed (**Cc** and **B2** according to Scheme 1), which then convert completely to **AH**$^+$ in a few seconds. At pH 7.0, the decrease of absorbance in the 300–400 nm region, corresponding to the disappearance of **Ct**, is not accompanied by an increase in absorbance in the visible region because in neutral solution **AH**$^+$ is not stable and the main products of the photoreaction are **B2** and **Cc** (Fig. 2). None of the thermal and photochemical processes observed are affected by the presence of oxygen in the solution and the degree of reversibility of the system is satisfactory.[19]

In conclusion, the photochemical behaviour is in very good agreement with the behaviour observed by pH jump experiments. Although **Cc** is obviously the primary product of flash excitation, the observed species and their survival time (from seconds to years) before going back to the thermodynamically stable form **Ct** depend on temperature and pH.

Flavylium ions with OH substituents

In flavylium compounds that carry an OH substituent in the 4′- and/or 7-positions other forms, not present in the above discussed 4′-methoxyflavylium compound, can be obtained because of the deprotonation of the OH group, as illustrated in Scheme 2 for the 4′-hydroxyflavylium ion.[21] The new species are the quinoidal base **A**, obtained by simple deprotonation of the **AH**$^+$ flavylium cation, and the dianionic **Cc**$^{2-}$ and **Ct**$^{2-}$ forms, obtained by second deprotonation of **Cc** and **Ct**. The roles played by these forms depend on the specific compound and pH conditions. For example, in the case of 4′-hydroxyflavilium ion the **Ct**$^{2-}$ species exhibits fluorescence and the **Cc**$^{2-}$ one undergoes photoisomerization to **Ct**$^{2-}$ (*vide infra*).[21] Interestingly, for the 4-methyl-7-hydroxy- and 4′,7-dihydroxyflavylium compounds both the **AH**$^+$ cation and the **A** quinoidal base exhibit fluorescence. Moreover, in the former compound, for which only two forms (**AH**$^+$ and **A**) are observed, the pK_a of the ground state (4.4) is higher than the apparent pK_a of the excited state (0.7) and a very efficient adiabatic excited state proton transfer reaction (yield = 0.95) transforms **AH**$^{+*}$ into **A***. These results show that 4-methyl-7-hydroxyflavylium behaves as a four-level system and suggests that it could be used, in principle, to obtain a laser effect.[20]

Energy level diagrams

As discussed above for the 4′-methoxyflavylium compound, pH jump, temperature jump, and flash photolysis experiments allow the measurement of the rate constants of some of the reactions involved, and steady state titration experiments (by using UV–VIS and NMR techniques) allow the measurement of equilibrium constants. The values obtained for the most important processes of four flavylium compounds are gathered in Table 1.

From an operative viewpoint, the complex equilibria involving the species present at moderately acid pH (Scheme 2) can be described in terms of a single acid–base equilibrium between the acid species **AH**$^+$ and a conjugated base '**CB**' having a concentration equal to the sum of the concentrations of the species **A**, **B4**, **B2**, **Cc** and **Ct** [eqn. (1)],

$$\mathbf{AH^+} \xrightleftharpoons{K_a'} \mathbf{'CB'} + \mathrm{H^+} \qquad (1)$$

where $K_a' = K_a + K_h + K_h^4 + K_hK_t + K_hK_tK_i$. The equilibrium constant of such an overall process is also given in Table 1. By using the data shown in Table 1, an energy level diagram can be constructed for each compound. Simplified versions of such diagrams (*e.g.* Fig. 4) can then be used to illustrate the behaviour of the various compounds[18–23] and to discuss the effect of the substituents.[22]

An intuitive way to describe the interconversion processes in flavylium-type compounds is their description using an hydraulic analogy.[22] Using such an analogy, the behaviour of an aqueous solution of flavylium ions upon a pH jump from 1.0 to 4.2 can be schematically represented as in Fig. 5. In the case of 4′-hydroxyflavylium, **Cc** converts very slowly to **Ct** and thus **B2** and **Cc** accumulate, whereas for 4′,7-dihydroxyflavylium and 7-hydroxyflavylium **Cc** converts very rapidly to **Ct** so that **Cc** and **B** disappear as soon as they are formed.

The hydraulic analogy can also be used to illustrate the photochemical behaviour of these compounds, the light playing the role of a pump. The scheme shown in Fig. 6 is appropriate for 4′-hydroxyflavylium.[22]

Properties of the network of chemical processes

As mentioned in the introduction, molecular or supramolecular systems capable of existing in different forms (*multistate*) that can be interconverted by different external stimuli (*multifunctional*) are interesting for both basic and application reasons. As we have seen above, the flavylium compounds can be interconverted into a number of different transient and stable forms using two different inputs, namely light or changes in pH. Several interesting aspects emerge when the resulting networks of chemical processes are analyzed in terms of 'molecular-level devices' and 'molecular level logic functions'. To illustrate these aspects, we will discuss the case of the 4′-hydroxyflavilylium compound (Scheme 1, $R^4 = R^7 = H$ and $R^{4'} = OH$; Fig. 4). For the sake of simplicity, in the following discussion the **A**, **B4** and **B2** transient species have been neglected since in the compound under examination they are always in rapid equilibrium with either **AH**$^+$ or **Cc**.

A write-lock-read-unlock-erase cycle

It is well known that photochromic systems represent potential molecular-level memory devices.[10–12] A number of problems, however, must be solved for practical applications. A most challenging one is to find systems with multiple storage and non-destructive readout capacity, *i.e.* the record can be erased when necessary, but is not destroyed by the readout. The 4′-hydroxyflavylium ion[21] (as well as the 4′-methoxyflavilium ion)[19] can be taken as the basis for an optical memory system with multiple storage and non-destructive readout capacity through a *write-lock-read-unlock-erase* cycle. This behavior can be described making reference to Figs. 4 and 7:

(i) At pH 4–7, the stable or kinetically inert (depending on pH) colorless **Ct** species can be photochemically converted (365 nm light) into the thermodynamically unstable, but relatively inert, **Cc** form (*write*).
(ii) Using a second stimulus (addition of acid), **Cc** can be converted into the kinetically inert or thermodynamically stable (depending on pH) **AH**$^+$ form (*lock*); if the initial pH is 1, the **Cc** species autolocks as **AH**$^+$.
(iii) The **AH**$^+$ species is photochemically inactive and shows an absorption spectrum clearly distinct from that of **Ct**, so that it can be optically detected (*read*).
(iv) Upon addition of base, **AH**$^+$ can be reconverted into **Cc** (*unlock*).
(v) **Cc** can be reconverted to the initial **Ct** form by a thermal or a photochemical reaction (*erase*).

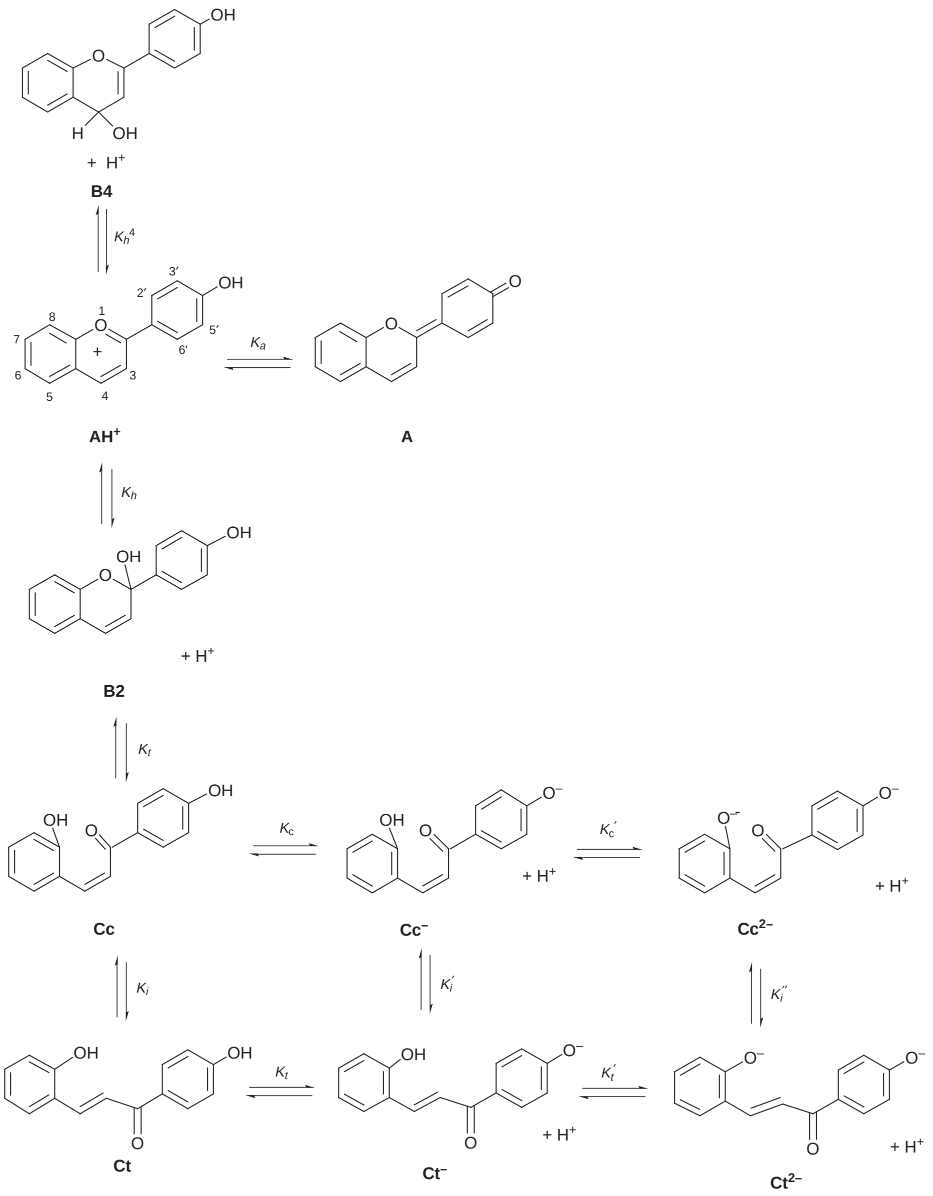
Reading without writing in a write-lock-read-unlock-erase cycle

A generally overlooked difficulty with photochromic systems is that the starting form (**Ct** in the above discussion) is the photoreactive one, so that it cannot be read by absorption spectroscopy without writing. With the 4′-hydroxyflavylium ion, this difficulty can be overcome starting from **AH**$^+$, which is the thermodynamically stable form at pH 1 (Figs. 4 and 8).[21] Since this form is not photosensitive, it can be read by light excitation (*i.e.* by recording its absorption spectrum) without writing. Then it can be unlocked by a pH jump to 12 which yields the metastable **Cc**$^{2-}$ form. At this stage, one can write the optical information obtaining the stable (locked) **Ct**$^{2-}$ form that can then be read. When necessary, the information stored into

Table 1 Thermodynamic and kinetic constants for the structural transformations of some synthetic flavilium compounds[a]

	Flavylium ion			
Parameter	7-OH[b]	4′,7-(OH)$_2$[c]	4′-OH[d]	4′-OMe[e]
K_a'	2.0×10^{-3}	8.9×10^{-4}	1.26×10^{-2} [f]	8.0×10^{-2}
K_a	2.8×10^{-4}	1.0×10^{-4}	3.16×10^{-6}	
K_h	8.0×10^{-6}	1.4×10^{-6}	3.6×10^{-6}	3.4×10^{-5}
K_t	—	—	1	0.50
K_i	5.0×10^{2}	1.4×10^{3}	3.5×10^{3}	*ca.* 10^{2}
k_h/s^{-1}	0.48	1.8×10^{-2}	8.9×10^{-2}	0.47
$k_{-h}/\mathrm{s}^{-1}\ \mathrm{M}^{-1}$	3×10^{4} [g]	1.3×10^{4} [g]	2.5×10^{4} [g]	1.38×10^{4}
k_i/s^{-1}	0.57 [g]	0.26 [g]	3.7×10^{-5}	5.8×10^{-5}
k_{-i}/s^{-1}	8.3×10^{-4}	1.8×10^{-4}	$< 10^{-7}$	$< 10^{-6}$

[a] Measured by means of pH jump techniques at 25 °C, unless otherwise noted. [b] Ref. 22. [c] Ref. 18. [d] Refs. 17 and 21. [e] Refs. 16 and 19. [f] At 60 °C. [g] Measured by flash photolysis.



Scheme 2 Structural transformations of the 4′-hydroxyflavylium compound.

Ct^{2-} can be unlocked by a pH jump yielding **Ct** and can then be erased by light excitation. The same performance can be obtained starting from Ct^{2-}.

Permanent and temporary memories

In our brain there are shallow and deep memory forms.[30] The network of processes interconverting the various species of the 4′-hydroxyflavylium ion allows the presence of different levels of memory.[21] Once the permanent (deep) AH^+ form of memory has been obtained (*write* and *lock*, Fig. 9), a jump to pH 12 leads to the formation of a temporary (shallow) memory state, Cc^{2-}, whose spontaneous slow erasure to give the deep Ct^{2-} memory can be accelerated by light. Reset can then be accomplished by a back pH jump to pH 4.

Oscillating absorbance patterns

Another feature of the 4′-hydroxyflavylium ion should be emphasized.[21] Starting from AH^+, alternation of pH jump and light excitation causes oscillation patterns of absorbance at different wavelengths, as shown in Fig. 10. Such patterns may be interesting for signal generation purposes.

Logic operations

From a logic viewpoint,[6,7,9,31] simple (bistable) photochromic systems perform YES/NO functions. Multistate/multifunctional molecular-level systems can be taken as bases for more complex logic operations. Chemical systems capable to perform AND,[31] OR,[31] XOR,[32] and XNOR[33]logic operations at the molecular level have been recently reported. With the 4′-hydroxyflavylium compound, light excitation and pH jumps can be taken as inputs, and absorbance or fluorescence as outputs. Starting from the non-emitting **Ct** species, and taking the emission of AH^+ at 515 nm as output signal, a jump to pH 1 alone or light excitation alone are not able to generate the output, whereas when these two imputs are applied in series, the output is obtained (AND logic function).[21]

Multiple reaction patterns

It can be interesting to observe that in the network of processes of the 4′-hydroxyflavylium compound some species are interconnected by multiple reaction patterns.[21] For example, in order to go from AH^+ to **Ct** three different routes can be chosen (Fig. 11). (i) A jump to pH 12 with formation of Cc^{2-}, followed by excitation with 313 nm light to obtain Ct^{2-}, and a jump to pH 6. (ii) A jump to pH 6 to form **Cc**; at this stage, one can choose between two sub-routes, *i.e.* (iia) light excitation with 313 nm

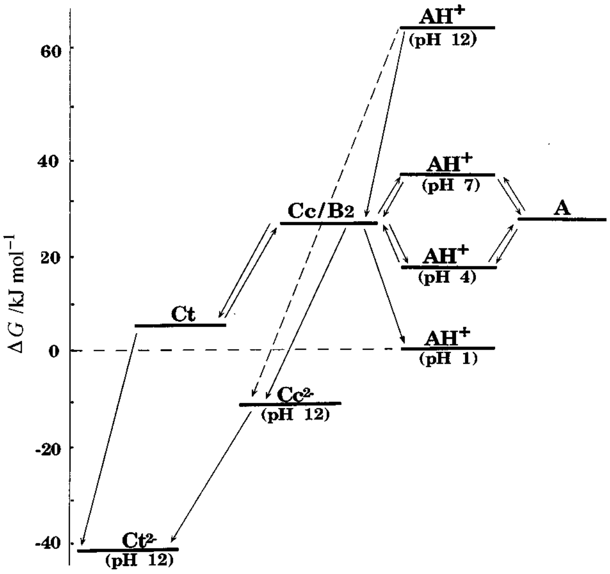


Fig. 4 Energy level diagram for the species involved in the pH jump and flash-photolysis experiments carried out on the 4′-hydroxyflavylium compound. pH values are indicated in brackets. For the sake of simplicity the species **Cc** and **B2** are represented by the same energy level. The ratio between the concentrations of **Cc** and **B2** is *ca.* 1. Reprinted with permission from ref. 21.

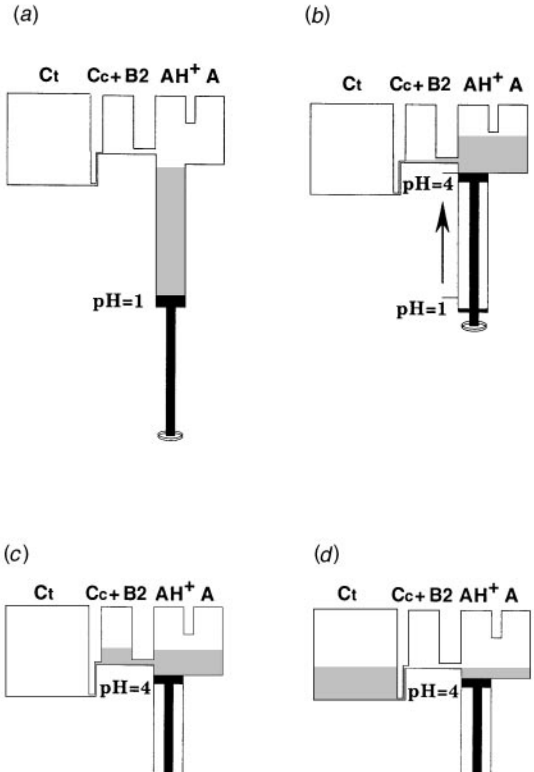


Fig. 5 Hydraulic analogy for a pH jump from pH 1.0 to 4.0: (*a*) the system is equilibrated at pH 1.0; (*b*) the system has been taken to pH 4.0; the pH jump has an effect comparable to raising the piston and the figure represents the situation immediately after the proton transfer process; (*c*) when the *cis*→*trans* isomerization is very slow it is possible to obtain an intermediate (pseudo-equilibrium) state involving the species **AH**$^+$, **A**, **B2** and **Cc**; (*d*) thermodynamic equilibrium at pH 4.0. Reprinted with permission from ref. 22.

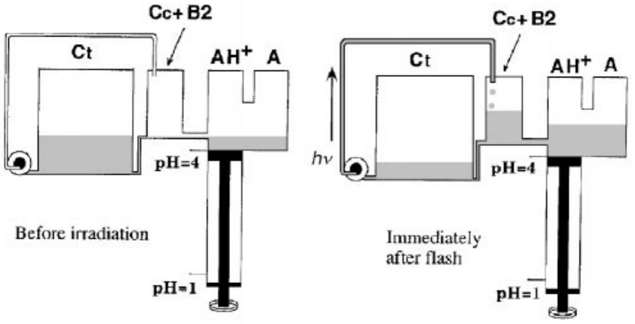


Fig. 6 Hydraulic analogy for the photochemical reaction of **Ct**. Light behaves like a pump that increases (in a transient mode as represented, or in steady state) the quantity of liquid in the reservoir **Cc**. Reprinted with permission from ref. 22.

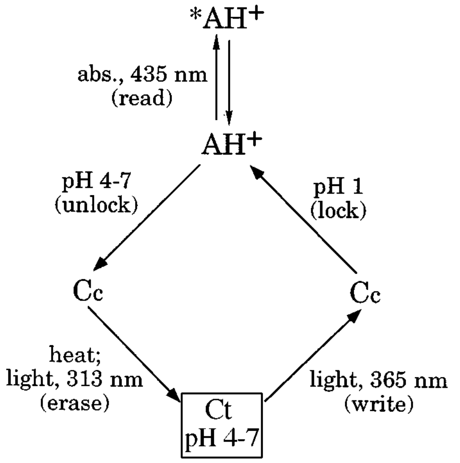


Fig. 7 Write-lock-read-unlock-erase cycle starting from the **Ct** form of the 4′-hydroxyflavylium compound. Reprinted with permission from ref. 21.

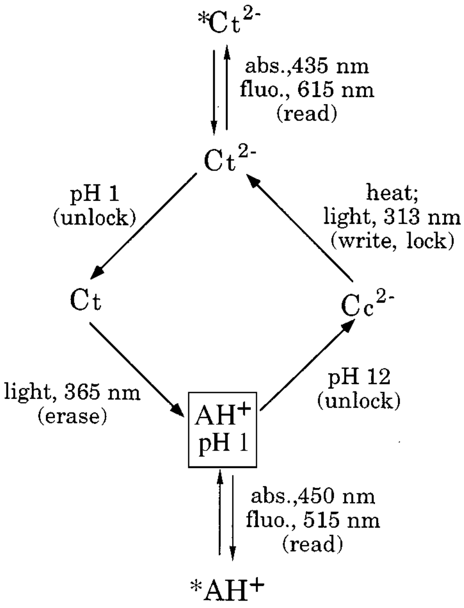


Fig. 8 Read-write-lock-read-unlock-erase cycle starting from the **AH**$^+$ form of the 4′-hydroxyflavylium compound. Reprinted with permission from ref. 21.

light, or (iib) a jump to pH 12 to merge into the preceeding path which goes *via* **Cc**$^{2-}$and **Ct**$^{2-}$. Once **Ct** has been obtained, one can go back to **AH**$^+$ by two different routes: (iii) light excitation at 365 nm to obtain **Cc** and subsequent jump to pH 1, or, *vice versa*, (iv) a jump to pH 1 and subsequent light excitation at 365 nm. Interestingly, in some cases, *i.e.* starting from **Ct** at pH 6, one obtains the same result (**AH**$^+$) regardless of the order in which light excitation (365 nm) and the pH jump (pH 1) are applied. In other cases, however, this is not true. For example (not shown in Fig. 11), starting from **AH**$^+$ at pH 1, light excitation followed by a pH jump to pH 12 leads to **Cc**$^{2-}$,

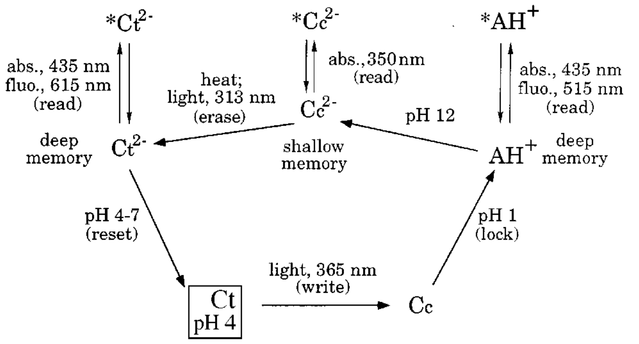


Fig. 9 A write-lock-read-unlock-erase cycle with two memory levels based on the 4′-hydroxyflavylium compound. Reprinted with permission from ref. 21.

whereas when the two inputs are applied in the reverse order one gets **Ct**$^{2-}$. Since **Cc**$^{2-}$ and **Ct**$^{2-}$ exhibit very different spectroscopic properties (*e.g.* **Ct**$^{2-}$ exhibits fluorescence whereas **Cc**$^{2-}$ does not), from the state of the systems after the two inputs one can establish in which sequence the two inputs have been applied.

Color-tap effect

Because of the competition between the pH dependent rate of the reaction leading from the uncoloured **Cc** form to the colored **AH**$^+$ and **A** species and the pH independent back *cis* → *trans* isomerization, the amount of colored species formed upon light excitation depends on the pH of the solution. In other words, the pH of the solution plays the role of a tap for the color intensity generated by light excitation.[22] This also means that this system can be viewed as a light-switchable pH indicator. In the case of 4′,7-dihydroxyflavylium the color-tap effect is larger than for 7-hydroxyflavylium.

Conclusions

Synthetic flavylium compounds can exist in several forms (*multistate*) that can be interconverted by more than one type of external stimulus (*multifunctional*). The intricate network of their reactions, when examined from the view points of ‘molecular-level devices’ and ‘molecular level logic functions’, reveal that these systems exhibit very interesting properties.

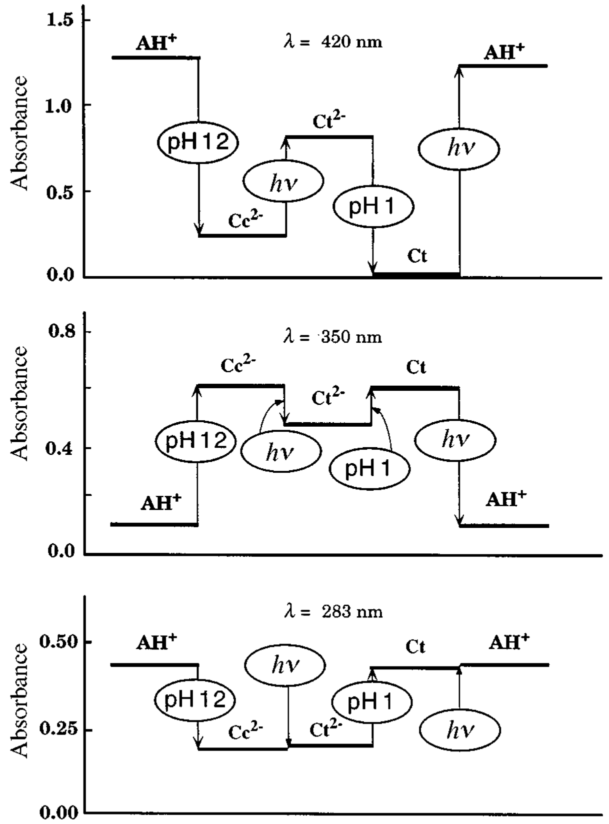


Fig. 10 Absorbance oscillations caused by alternate pH jump and light excitation on a 3.3 × 10^{-5} M aqueous solution starting from the **AH**$^+$ form of the 4′-hydroxyflavylium compound at pH 1. Reprinted with permission from ref. 21.

In our brain, neurons store, exchange, and retrieve information *via* extremely complicated chemical processes. Synthetic multistate/multifunctional systems may play the role of models to begin understanding the chemical basis of complex biological processes. It is not at all clear whether ‘wet’ artificial systems can find real applications, for example in molecular-scale computers.[34] However, the study of molecular or supramolecular species capable of existing in different forms that can be interconverted by external stimuli is a topic of great interest since it introduces new concepts into the field of chemistry and

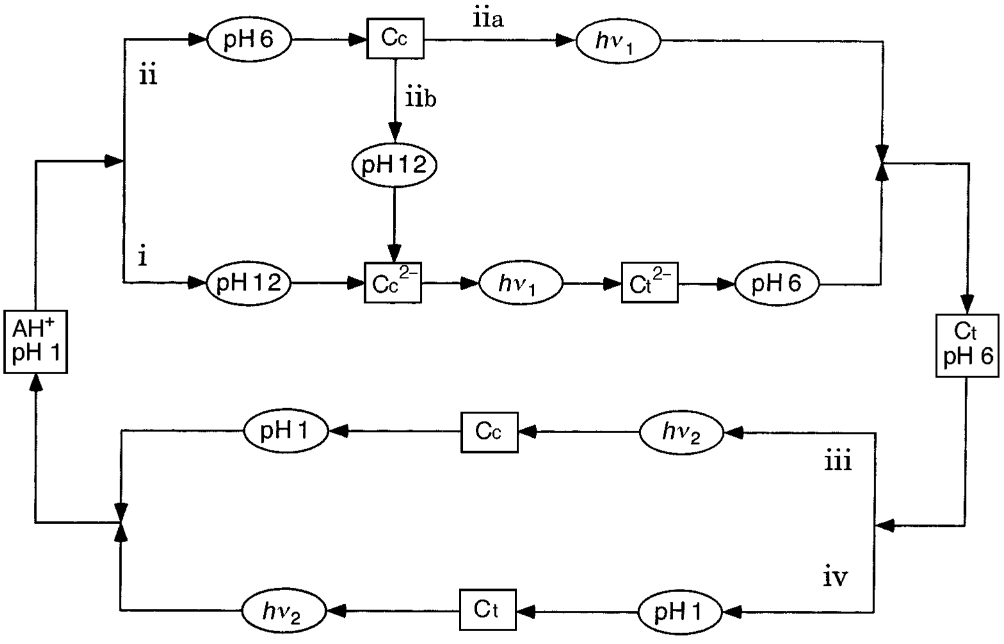


Fig. 11 The network of processes caused by pH jumps and light excitations interconnecting the **AH**$^+$ and **Ct** forms of the 4′-hydroxyflavylium compound. Reprinted with permission from ref. 21.

stimulates the ingenuity of research workers engaged in the ‘bottom up’ approach to nanotechnology.

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