

Multistate/Multifunctional Systems. A Thermodynamic, Kinetic, and Photochemical Investigation of the 4'-Dimethylaminoflavylum Compound

Ana Roque,[†] Carlos Lodeiro,[†] Fernando Pina,^{*,†} Mauro Maestri,^{*,‡} Stephane Dumas,[‡] Paolo Passaniti,[‡] and Vincenzo Balzani[†]

Contribution from the Departamento de Química, Centro de Química-Fina e Biotecnologia, Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Quinta da Torre, 2825-Monte de Caparica, Portugal, and Dipartimento di Chimica "G. Ciamician", Università di Bologna, 40126 Bologna, Italy

Received September 27, 2002; E-mail: mmaestri@ciam.unibo.it

Abstract: The 4'-dimethylaminoflavylum ion in aqueous solution undergoes an intricate network of chemical reactions controlled by pH and light excitation. It is shown that nine different forms are involved, including two species that are not present in previously investigated compounds of the flavylum family. The thermodynamic and kinetic constants of the equilibria and interconversion processes have been obtained by pH jump (included stopped-flow) experiments. The photochromic properties exhibited by the trans/cis chalcone forms have been investigated. The peculiar aspect of 4'-dimethylaminoflavylum, as compared to previously investigated compounds of the same family, is a close to planarity structure, as demonstrated by the X-ray analysis on the parent 4'-aminoflavylum compound (2.3° torsion angle between the benzopyrylium and benzene ring). The results obtained show that the flavylum cation is strongly stabilized by the electron-donor character of the dimethylamino substituent on the benzene ring. The donor–acceptor interaction makes both the protonation of the amino group and the hydration of the flavylum cation difficult, with consequences on the tautomerization and cis/trans isomerization reactions. The multistate/multifunctional properties of 4'-dimethylaminoflavylum have been discussed in the frame of write–lock–read–unlock–erase cycles.

Introduction

By using a single input on a chemical compound, one can play with two states. When more than one input is used, the number of available states increases, leading to systems capable of performing complex functions. On the application of n independent stimuli, each one related to a couple of states, $2n$ different states of the systems become available in principle. A number of compounds have recently been described in which different stimuli have been used to interconvert several states.^{1,2} Systems which respond to a given combination of multiple stimuli open the way to complex switches (logic gates) at the molecular scale.³

Because of the presence of a 2-phenyl-benzopyrylium core, synthetic flavylum salts,^{4–9} as well as natural anthocyanins,^{10,11} can be involved in intricate networks of chemical transformations in aqueous solution. Such transformations follow a general pattern, schematized in Figure 1, which involves four main species: a flavylum cation AH^+ , a hemiacetal species **B2** obtained by hydration in the 2 position of the flavylum cation,

[†] Universidade Nova de Lisboa.

[‡] Università di Bologna.

- (1) For reviews, see: (a) Niemz, A.; Rotello, V. M. *Acc. Chem. Res.* **1999**, *32*, 44. (b) Kaifer, A. E. *Acc. Chem. Res.* **1999**, *32*, 62. (c) Balzani, V.; Credi, A.; Raymo, F. M.; Stoddart, J. F. *Angew. Chem., Int. Ed.* **2000**, *39*, 3348. (d) *Molecular Switches*; Feringa, B. L., Ed.; Wiley-VCH: Weinheim, 2001.
- (2) For some leading papers, see: (a) Irie, M.; Miyatake, O.; Uchida, K.; Eriguchi, T. *J. Am. Chem. Soc.* **1994**, *116*, 9894. (b) Kawai, S. H.; Gilat, S. L.; Posinet, R.; Lehn, J.-M. *Chem.-Eur. J.* **1995**, *1*, 285. (c) Speitzer, H.; Daub, J. *Chem.-Eur. J.* **1996**, *2*, 1150. (d) Plenio, H.; Aberle, C. *Angew. Chem., Int. Ed.* **1998**, *37*, 1397. (e) Ji, H.-F.; Dabestani, R.; Brown, G. M. *J. Am. Chem. Soc.* **2000**, *122*, 9306. (f) Goodman, A.; Breinlinger, E.; Ober, M.; Rotello, V. M. *J. Am. Chem. Soc.* **2001**, *123*, 6213. (g) Gobbi, L.; Seiler, P.; Diederich, F. *Angew. Chem., Int. Ed.* **1999**, *38*, 674. (h) Gobbi, L.; Seiler, P.; Diederich, F.; Gramlich, V.; Boudon, C.; Gisselbrecht, J.-P.; Gross, M. *Helv. Chim. Acta* **2001**, *84*, 743. (i) Bourgel, C.; Boyd, A. S. F.; Cooke, G.; Augier de Creliers, H.; Duclairon, F. M. A.; Rotello, V. M. *Chem. Commun.* **2001**, 1954. (j) Zhao, W.; Carreira, E. M. *J. Am. Chem. Soc.* **2002**, *124*, 1582.

- (3) (a) de Silva, A. P.; Gunaratne, H. Q. N.; Gunnlaugsson, T.; Huxley, A. J. M.; McCoy, C. P.; Rademacher, J. T.; Rice, T. E. *Chem. Rev.* **1997**, *97*, 1515. (b) Balzani, V.; Credi, A.; Venturi, M. In *Supramolecular Science: Where It is and Where It is Going*; Ungaro, R.; Dalcanale, E., Eds.; Kluwer: Dordrecht, 1999; p 1. (c) de Silva, A. P.; Fox, D. B.; Moody, T. S. In *Stimulating Concepts in Chemistry*; Shibasaki, M.; Stoddart, J. F., Vögtle, F., Eds.; Wiley-VCH: Weinheim, 2000; p 307. (d) Pease, A. R.; Stoddart, J. F. *Struct. Bonding* **2001**, *99*, 189. (e) de Silva, A. P.; McClenaghan, N. D.; McCoy, C. P. In *Molecular Switches*; Feringa, B. L., Ed.; Wiley-VCH: Weinheim, 2001; p 339. (f) Raymo, F. M. *Adv. Mater.* **2002**, *14*, 401. Stojanovic, M. N.; Mitchell, T. E.; Stefanovic, D. *J. Am. Chem. Soc.* **2002**, *124*, 3555 and references therein.
- (4) McClelland, R. A.; Gedge, S. *J. Am. Chem. Soc.* **1980**, *102*, 5838.
- (5) McClelland, R. A.; McGall, G. H. *J. Org. Chem.* **1982**, *47*, 3730.
- (6) Figueiredo, P.; Lima, J. C.; Santos, H.; Wigand, M.-C.; Brouillard, R.; Maçanita, A.; Pina, F. *J. Am. Chem. Soc.* **1994**, *116*, 1249.
- (7) Brouillard, J. R.; Dubois, J. E. *J. Am. Chem. Soc.* **1977**, *99*, 1359.
- (8) Pina, F.; Maestri, M.; Balzani, V. *J. Chem. Soc., Chem. Commun.* **1999**, 107.
- (9) Maestri, M.; Pina, F.; Balzani, V. Multistate/Multifunctional Molecular-Level Systems – Photochromic Flavylum Compounds. In *Molecular Switches*; Feringa, L. B., Ed.; Wiley-VCH: Weinheim, 2001; p 339.
- (10) Brouillard, R. In *The Flavonoids, Advances in Research*; Harborne, J. B., Ed.; Chapman and Hall: London, 1988; p 525.
- (11) Brouillard, R. In *Anthocyanins as Food Colors*; Markakis, P., Ed.; Academic Press: New York, 1982; Chapter 1.

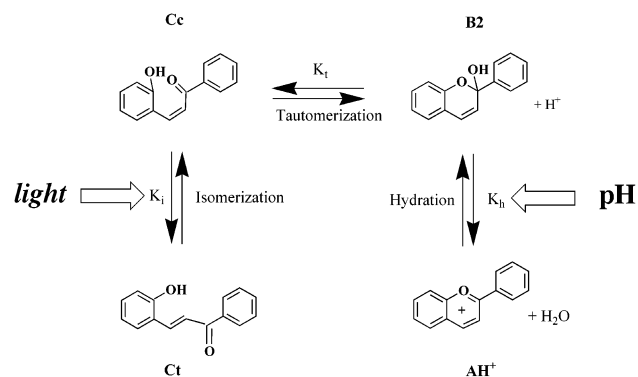


Figure 1. Structural transformations of the flavylium-type compounds. Only the most important forms are shown.

a *cis*-2-hydroxychalcone **Cc** formed by tautomerization of **B2**, and a *trans*-2-hydroxychalcone **Ct** obtained by isomerization of **Cc**. Because the hydration and isomerization equilibria can be displaced by two different stimuli (pH and light, respectively) and are coupled by a tautomeric process, flavylium compounds are interesting examples of multistate/multifunctional systems that, in principle, can be used for information processing at the molecular level.^{8,9,12–15}

Systematic studies^{4–9,12–26} showed that, when suitable substituents are present in the 4'-position, the flavylium-based compounds, under the combined action of acid/base and light stimuli, undergo write–lock–read–unlock–erase photochromic cycles,^{12–14,20,21,25} perform as XOR²³ and XNOR¹⁵ logic gates, and can exhibit other interesting multistate/multifunctional properties.^{8,9} From a chemical viewpoint, such studies have evidenced the following features: (i) all of the examined compounds follow the basic scheme shown in Figure 1; (ii) other species can be involved, depending on the presence of substituents; (iii) the thermodynamic constants of the various equilibria, the kinetic constants of the thermal reactions, and the quantum yield of the photoisomerization reactions are strongly affected by the nature and position of substituents; and (iv) the energy barrier of the *cis*–*trans* isomerization, which is an important parameter for information processing, increases by hydroxylation in the 3' and 4' positions and decreases when a hydroxyl group is present in positions 5 or 7. The complexity that can be reached by these systems is well exemplified by the 4'-hydroxyflavylium

compound (Figure 2), which can be present in as many as 10 different forms.¹³

Looking at Figure 2, we note that (a) water can attack the 4 position, leading to the formation of hemiacetal **B4** (usually formed in very small amounts, <1%); (b) OH substituents in the 4' (or 7) position undergo deprotonation, giving rise to a quinoidal base, **A**; (c) in basic solution, the OH groups of the **Cc** and **Ct** forms undergo deprotonation (in the absence of OH substituents, only monoanionic species are formed).

Continuing our studies in this field, we have investigated the behavior of a flavylium compound carrying the electron-donating dimethylamino substituent in the 4' position (Figure 3).

Some aspects of the photochromic reaction of this compound in water–ethanol solution and in polymer media have been previously reported by Matsushima et al.²⁷ In this paper, we report the results obtained in acidic, neutral, and basic solutions by conventional, stopped-flow, and photochemical techniques. We have established the number of species involved in the chemical transformations of this compound, and we have obtained the thermodynamic and kinetic constants of the various processes and elucidated the effect of continuous and pulsed irradiation. Attempts to prepare crystals of 4'-dimethylaminoflavylium suitable to obtain a X-ray structure failed, but we have resolved the structure of the analogous 4'-aminoflavylium compound. This result has allowed us to better understand the reason why 4'-dimethylaminoflavylium displays quite peculiar features as compared with previously investigated compounds of the same family. Finally, we have shown that the dimethylamino substituent in the 4' position is quite useful to improve the multistate/multifunctional properties of the flavylium ion.

Results and Discussion

Structure. As mentioned above, we were unable to obtain good crystals of 4'-dimethylaminoflavylium salts, both with tetrafluoroborate and with hexafluorophosphate anions. It was possible, however, to obtain crystals of the 4'-aminoflavylium ion as hexafluorophosphate salt and to determine its X-ray structure. As one can see from Figure 4, the 4'-aminoflavylium ion is almost planar, including the hydrogen atoms of the amine group.

The most interesting features of this structure (details are given as Supporting Information) are (i) the short bond length between carbon C14 (4') and nitrogen (1.354 Å)²⁸ and (ii) the small value (2.3°) of the torsion angle between the pyrylium and benzene ring. Note that such a torsion angle is 5.9° and 10.1° for 4',6,7-trihydroxyflavylium²⁹ and 3,3',4',5,7-pentahydroxyflavylium,³⁰ respectively, and 40.7° in the case of 3-methylflavylium²⁵ because the methyl substituent in the 3 position forces the phenyl ring out of planarity. According to the X-ray results, the C4'–N bond of the 4'-aminoflavylium ion possesses a noticeable double bond character, so that its most realistic

- (12) Pina, F.; Melo, M. J.; Maestri, M.; Ballardini, R.; Balzani, V. *J. Am. Chem. Soc.* **1997**, *119*, 5556.
 (13) Pina, F.; Roque, A.; Melo, M. J.; Maestri, M.; Belladelli, L.; Balzani, V. *Chem.-Eur. J.* **1998**, *4*, 1184.
 (14) Pina, F.; Melo, M. J.; Passaniti, P.; Camaioni, N.; Maestri, M.; Balzani, V. *Eur. J. Org. Chem.* **1999**, *11*, 3199.
 (15) Roque, A.; Pina, F.; Alves, S.; Ballardini, R.; Maestri, M.; Balzani, V. *J. Mater. Chem.* **1999**, *9*, 2265.
 (16) Pina, F.; Melo, M. J.; Flamigni, L.; Ballardini, R.; Maestri, M. *New J. Chem.* **1997**, *21*, 969.
 (17) Maestri, M.; Ballardini, R.; Pina, F.; Melo, M. J. *J. Chem. Educ.* **1997**, *74*, 1314.
 (18) Pina, F. *J. Chem. Soc., Faraday Trans.* **1998**, *94*, 2109.
 (19) Pina, F.; Melo, M. J.; Santos, M. H.; Lima, J. C.; Abreu, I.; Ballardini, R.; Maestri, M. *New J. Chem.* **1998**, 1093.
 (20) Pina, F.; Melo, M. J.; Parola, A. J.; Maestri, M.; Balzani, V. *Chem.-Eur. J.* **1998**, *4*, 2001.
 (21) Maestri, M.; Pina, F.; Roque, A.; Passaniti, P. *J. Photochem. Photobiol., A* **2000**, *137*, 21.
 (22) Melo, M. J.; Moura, S.; Roque, A.; Maestri, M.; Pina, F. *J. Photochem. Photobiol.* **2000**, *135*, 33.
 (23) Pina, F.; Melo, M. J.; Maestri, M.; Passaniti, P.; Balzani, V. *J. Am. Chem. Soc.* **2000**, *122*, 4496.
 (24) Pina, F.; Melo, M. J.; Alves, S.; Ballardini, R.; Maestri, M.; Passaniti, P. *New J. Chem.* **2001**, *25*, 747.
 (25) Roque, A.; Lodeiro, C.; Pina, F.; Melo, M. J.; Maestri, M.; Ballardini, R.; Balzani, V. *Eur. J. Org. Chem.* **2002**, 2699.

- (26) Melo, M. J.; Moura, S.; Maestri, M.; Pina, F. *J. Mol. Struct.* **2002**, *612*, 245.
 (27) Matsushima, R.; Mizuno, H.; Itoh, H. *J. Photochem. Photobiol., A* **1995**, *89*, 251.
 (28) Tables of Bond Lengths determined by X-ray and Neutron Diffraction. Part 1. Bond Lengths in Organic Compounds: Allen, F. H.; Kennard, O.; Watson, D. G.; Brammer, L.; Orpen, A. G.; Taylor, R. *J. Chem. Soc., Perkin Trans. 2* **1987**, S1–S19.
 (29) Ueno, K.; Saito, N. *Acta Crystallogr., Sect. B: Struct. Crystallogr. Cryst. Chem.* **1977**, *B33*, 111.
 (30) Ueno, K.; Saito, N. *Acta Crystallogr., Sect. B: Struct. Crystallogr. Cryst. Chem.* **1977**, *B33*, 114.

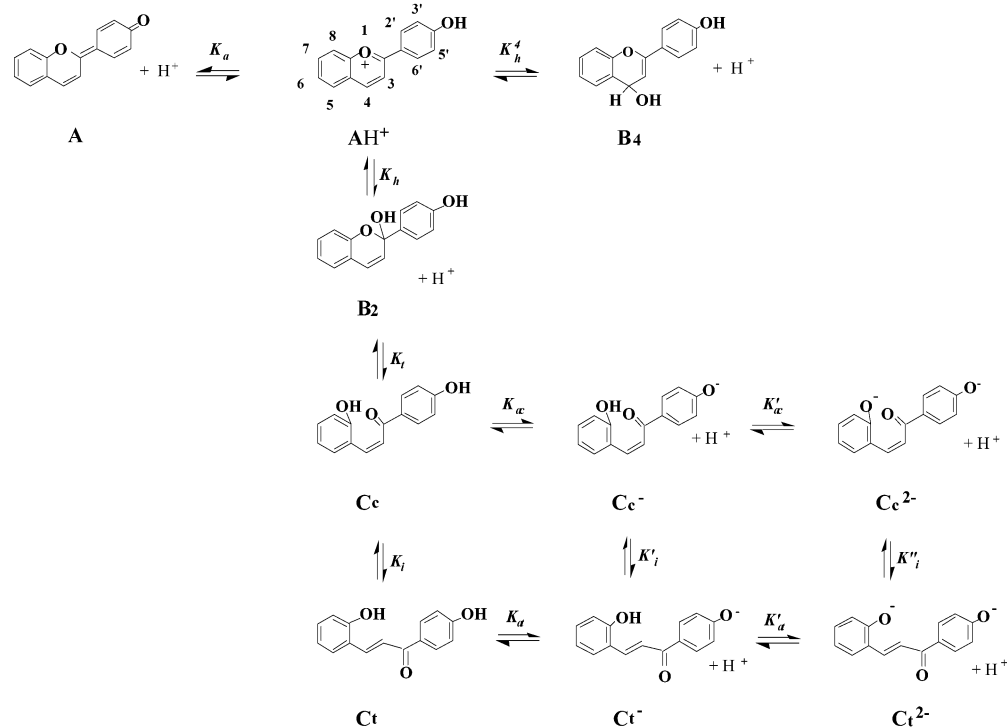


Figure 2. Complete scheme of the structural transformations taking place in the 4'-hydroxyflavylium compound.

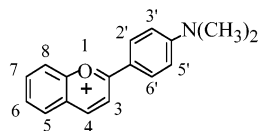


Figure 3. Structural formula of the 4'-dimethylaminoflavylium compound.

representation is structure II in Figure 5. Clearly, protonation of the amino nitrogen and nucleophilic attack on the pyrylium ion are expected to be difficult in such a structure. These conclusions can reasonably be extended to the 4'-dimethylaminoflavylium ion.

Nature of the Species Involved and Thermodynamic Aspects. The electronic absorption spectrum of 4'-dimethylaminoflavylium in acidic solution (pH 4.4) exhibits an intense band with $\lambda_{\max} = 535$ nm and $\epsilon = 35\,000$ M⁻¹ cm⁻¹ (Figure 6, curve a).

This band, which is displayed also in 1:1 water–ethanol solution,²⁷ is similar but somewhat red shifted as compared to that observed for the other flavylium compounds^{1,2,12–14} and can be assigned to the AH⁺ form (Figure 7). When the 4'-dimethylaminoflavylium ion is dissolved in 10 M HCl, the band at 535 nm can no longer be observed, and a strong band with $\lambda_{\max} = 385$ nm and $\epsilon = 30\,500$ M⁻¹ cm⁻¹ is present (Figure 6, curve b). In going from acidic to very acid solution and vice versa, immediate and progressive spectral changes with well defined isosbestic points are observed (Figure 6). These results show that the species exhibiting bands maxima at 535 and 385 nm are reversibly connected by a fast acid/base equilibrium and can therefore be identified as AH⁺ and its N-protonated AH²⁺ forms, respectively (Figure 7).

A plot of the absorbance change at 535 nm as a function of pH yielded a value of -0.6 for this acid–base equilibrium (pK_a). The 4'-aminoflavylium compound was found to exhibit the same behavior, with $pK_a = -0.4$, showing that the two compounds

have indeed quite similar properties. Comparison with the pK_a of aniline (4.63)³¹ and *p*-nitroaniline (1.0)³¹ shows that the pyrylium cation is a very strong electron-withdrawing group. These results fully agree with the above-discussed X-ray structure of 4'-aminoflavylium.

Starting from pH 2 (AH⁺ form), pH jumps to high pH values (4–12) evidenced the occurrence of at least two different processes. A process completed in 15 min leads to a pH-dependent decrease of the 535 nm band and the appearance of a new band with maximum at 370 nm (Figure 8). A plot of the absorbance changes at 535 nm versus pH yielded an apparent pK_a equal to 6.85 for this acid–base equilibrium.

¹H NMR experiments performed on basic solutions (8 < pH < 12) 15 min after the pH jump showed a single set of peaks, indicating that only one species (or more than one in fast equilibrium) is present. On a longer time scale (days), this set of peaks disappears, and at pH > 9.5, another single set of peaks is obtained. Spectrophotometric measurements show that reacidification to pH 1 of a solution equilibrated for 15 min at pH 9.5 leads to fast and complete recovery of AH⁺, whereas reacidification to pH 1 of a solution equilibrated for 15 days (in the dark) at pH 11 yields only 3% of AH⁺, again in a fast process. In agreement with the behavior previously observed for other flavylium species,^{1,2,12–14} it is possible to identify the first species, formed within 15 min, with the anionic *cis*-chalcone form Cc⁻, and the second species, formed after days, with the anionic *trans*-chalcone form Ct⁻ (Figure 7). These assignments are also supported by ¹H NMR experiments that show (i) a high field shift of the position of the peaks corresponding to protons 3 and 4 during the slow process (conversion of Cc⁻ to Ct⁻) and (ii) a scalar coupling constant of 15.6 Hz between protons 3 and 4 for the second species, a value fully consistent with a

(31) Lide, D. R. *Handbook of Chemistry and Physics*, 75th ed.; CRC: Boca Raton, FL, 1994.

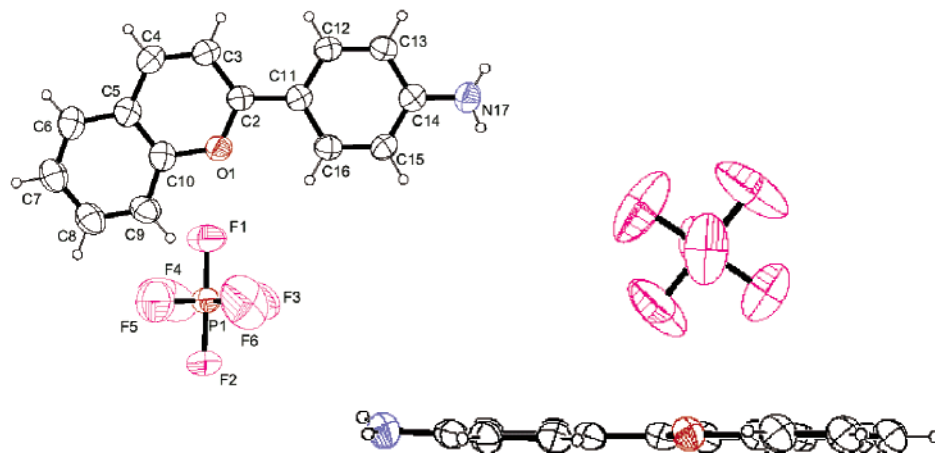


Figure 4. X-ray structure of a single crystal of the 4'-aminoflavylium compound (PF_6^- salt). Front view with atom label numbers (left) and side view (right).

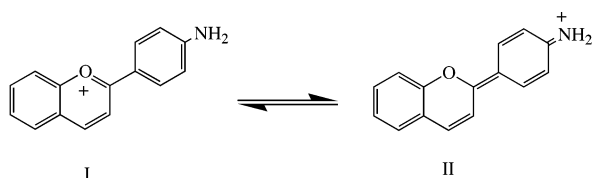


Figure 5. Resonance equilibria between two forms of the 4'-dimethylamino-flavylium cation. Form II is the most realistic one on the basis of the X-ray structure.

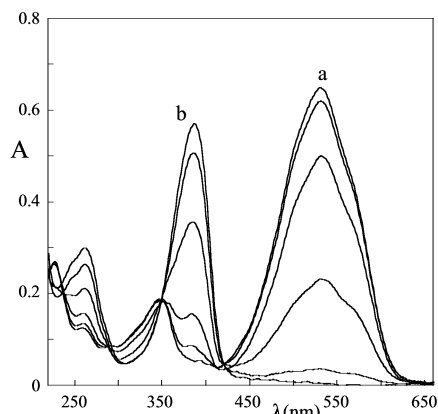


Figure 6. Absorption spectra of aqueous solutions of the 4'-dimethylamino-flavylium compound (2.1×10^{-5} M) as a function of pH: curve a is the absorption spectrum in the range 2–4, and curve b is the absorption spectrum at pH -0.9 .

trans configuration (compare with the value of 12.4 Hz for the cis isomer).³

The above results can be accounted for as follows (Figure 7). Upon a pH jump from pH 2 to pH > 4 , AH^+ undergoes hydration to form **B2** only at high pH values because of the strong electron-donating effect of the dimethylamino group. When hydration occurs (mainly by OH^- attack, see later), the pH is already high enough to deprotonate **Cc**, so that **B2** and **Cc** cannot accumulate. On a much longer time scale (days) and at pH > 9.5 , the stable species is Ct^- . The residual 3% conversion to AH^+ upon protonation shows that the isomerization reaction that converts **Cc** to Ct^- has an equilibrium constant (K_1') of ca. 30.

Once obtained after 15 days in the dark at pH 11.5, solutions of Ct^- were acidified to pH 5.0 and 0.5. Immediate spectral

changes were observed, showing the occurrence of fast acid/base processes. The spectra obtained are shown in Figure 9, together with the spectrum of the starting solution (pH 11.5).

The diversity of the three spectra clearly indicates that three different species exist for the trans configuration, an anionic (Ct^-), a neutral (**Ct**), and a cationic (Ct^+) species (Figure 7). Titration of the charged species (with acid in the case of Ct^- , with base in the case of Ct^+) has allowed us to obtain the equilibrium constants ($\text{p}K_{\text{at}}$ ca. 8 for Ct/Ct^- , $\text{p}K'_{\text{at}}$ ca. 2 for Ct^+/Ct).³² It is also interesting to note that once obtained at pH 1, Ct^+ very slowly converts (days time scale) completely to the starting AH^+ species, showing that the chemical transformations occurring in the system are fully reversible.

In conclusion, the pH jump experiments have allowed us to identify six different species, AH^+ , AH^{2+} , **Cc**⁻, Ct^- , **Ct**, and Ct^+ , stable enough to be characterized by conventional absorption spectroscopy experiments. The range of thermodynamic stability of these species depends on pH, and two of them, **Cc**⁻ and Ct^+ , are metastable, being converted in the time scale of days into Ct^- and AH^+ , respectively. The N-protonated species AH^{2+} and Ct^+ , of course, were not present in the previously investigated compounds of the flavylium family.

Kinetic Aspects. The thermodynamic equilibria discussed in the previous section do not fully account for the complexity of the examined system. Therefore, we have performed a detailed investigation on the kinetic processes connecting the various species by using conventional and stopped-flow spectroscopic techniques.

pH Jumps to Basic Solutions. Starting from solutions at pH 4.0, jumps to higher pH values cause the disappearance of AH^+ and the formation of **Cc**⁻ in a time scale of minutes. Plots of the spectral changes at 535 nm versus time showed that at all of the pH values higher than 7, the process follows a first-order kinetic whose rate constant increases with increasing pH (Table 1). This means that the rate-determining step must involve the participation of OH^- ions and can be identified with the hydration reaction that leads from AH^+ to **B2** and/or **B4**, occurring via OH^- attack on the 2 and/or 4 positions of the pyrylium moiety. Note that, in other flavylium systems, this hydration reaction can occur at much lower pH values and takes place by water attack of AH^+ .^{1,2,12–14}

(32) The low solubility of the **Ct** form prevented us to obtain more precise $\text{p}K_{\text{a}}$ values.

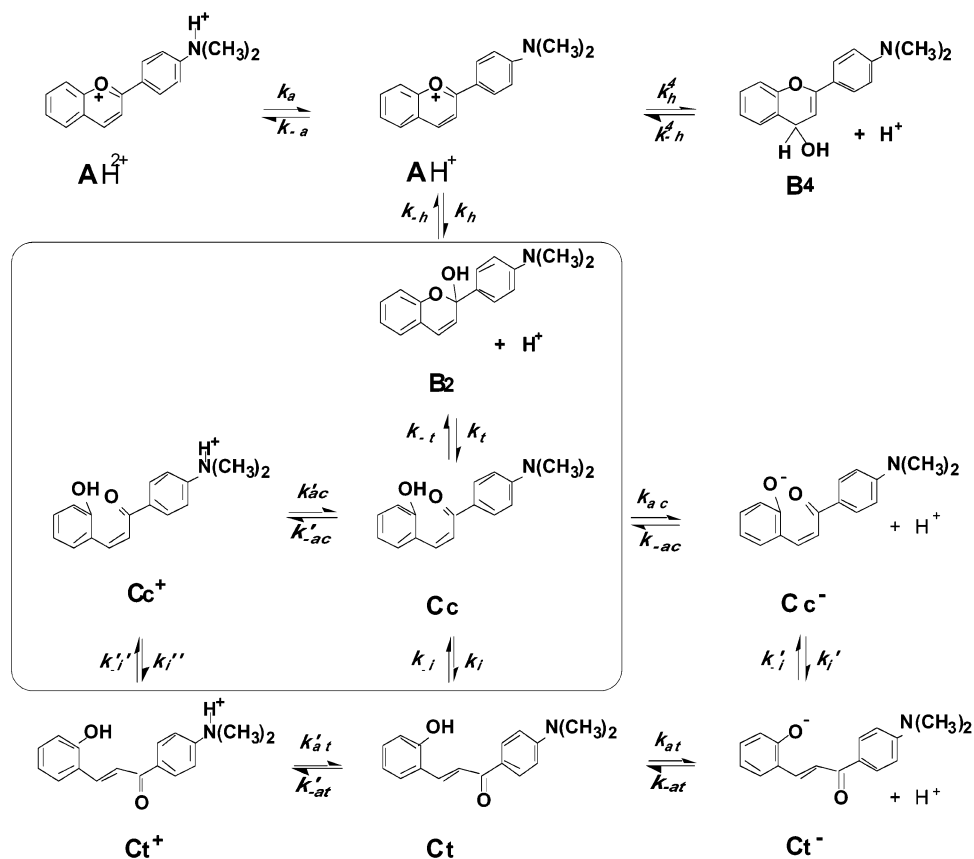


Figure 7. Structural transformations taking place in the 4'-dimethylaminoflavylum compound. The area within the square highlights the species that cannot be identified from the changes in absorption spectra.

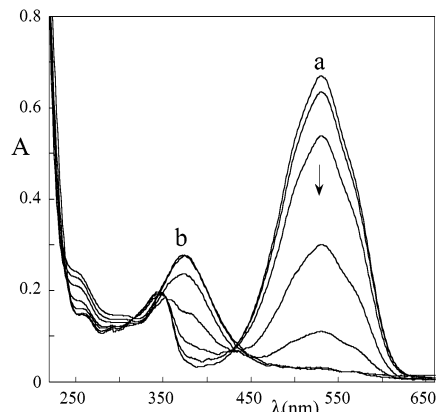


Figure 8. Spectral changes of aqueous solutions of 2.1×10^{-5} M 4'-dimethylaminoflavylum, 1 h after pH jumps from pH 2 to the pH range $4.4 < \text{pH} < 11.5$. Curves a and b are the spectra at pH 4.4 and 11.5, respectively.

The spectral changes obtained in the time scale of 1 s after the pH jump from 4.0 to 11.7 are shown in Figure 10a. The final spectrum (at 1 s) can be attributed to Cc^- except for a band around 290 nm, which indicates the presence of another species, provisionally indicated by **X**. After 200 s, the band at 290 nm disappears, and the band of Cc^- at 370 nm reaches its maximum (Figure 10b).

At this point, the system is in a pseudoequilibrium situation. The final equilibrium, which implies the conversion of Cc^- to Ct^- , is reached in a much longer (days) time scale (vide supra).

The transient species **X** can be assigned to the **B4** hemiacetal form (Figure 7), obtained upon hydration of the C4 position. It

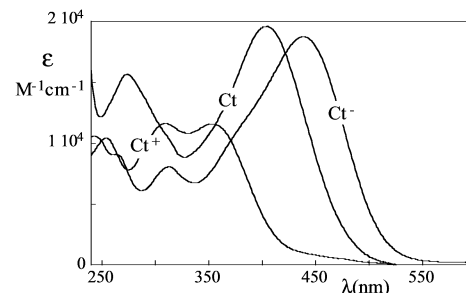


Figure 9. Absorption spectra as a function of pH of the trans species involved in the structural transformations of 4'-dimethylaminoflavylum at pH 11.5 (Ct^-), pH 6.0 (Ct), and pH 0.5 (Ct^+).

Table 1. Observed First-Order Rate Constants for the Kinetic Processes Occurring upon a pH Jump from pH 4.0 (AH^+) to Basic pH Values ($\text{pH} > 7$)

final pH	$k_{\text{obs}} (\text{s}^{-1})$
7.05	2.2×10^{-3}
7.83	2.5×10^{-3}
9.85	6.6×10^{-2}
11.70	7.8 and 1.8×10^{-2} ^a

^a Stopped-flow measurements.

seems likely that, after the pH jump, OH^- attacks both the C2 and the C4 positions, giving rise to the formation of both **B2** and **B4**. Therefore, the first-order rate constant observed for the disappearance of AH^+ on the time scale of 1 s ($k_{\text{obs}} = 7.8 \text{ s}^{-1}$) is likely the sum of the rate constants of the two parallel hydration reactions. **B2** is then thought to undergo fast conversion to Cc^- (via Cc) within the first second, whereas **B4** can be identified with the **X** species that converts to Cc^- in a few

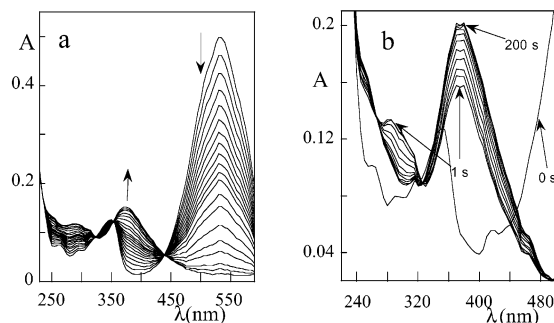


Figure 10. Spectral changes obtained by stopped-flow measurements upon a pH jump from pH 4.0 (AH^+) to 11.7: (a) spectral changes obtained within 1 s; (b) spectral changes obtained from 1 to 200 s.

minutes, probably via dehydration to AH^+ and then via **B2** and **Cc**. In this reasonable hypothesis, the ratio of the Cc^- absorption plateau after the fast and slower steps is proportional to the ratio between the concentrations of **B2** and **B4** formed from the disappearance of AH^+ , which is equal to the ratio of the respective rate constants. From the two equations

$$k_h + k_h^4 = 7.8 \text{ s}^{-1} \quad (1)$$

$$k_h/k_h^4 = [\text{B4}]/[\text{B2}] = 0.2 \quad (2)$$

one can obtain the following values for the hydration constants k_h and k_h^4 : $k_h = 6.5 \text{ s}^{-1}$ and $k_h^4 = 1.3 \text{ s}^{-1}$.

The decrease in absorbance at 290 nm on the time scale of 5 min follows a first-order kinetics with a rate constant of 0.018 s^{-1} , assigned to the rate-determining step of the process leading from **B4** to Cc^- , which is likely the rate constant of **B4** dehydration, k_{-h}^4 .

As we have seen above, solutions of 4'-dimethylaminoflavylum at pH 4 upon a pH jump to pH > 7 give rise in a few minutes to a pseudoequilibrium situation in which only the Cc^- form is present. On a much longer time scale, however, the system evolves toward a real equilibrium in which most of Cc^- has been converted into Ct^- . At pH 11 at room temperature, the rate constant for the disappearance of Cc^- is $3.0 \times 10^{-4} \text{ min}$, and the final equilibrium, with composition 97% Ct^- and 3% Cc^- , requires days to be established. At 60 °C, the rate constant is $2.1 \times 10^{-2} \text{ min}$, showing that the isomerization reaction has a considerable activation energy. For solutions at pH 8.7, an Arrhenius plot obtained from experiments performed at various temperatures yielded an activation energy of 81 kJ mol^{-1} .

Reverse pH Jumps. To gain more insight into the complex network of the chemical reactions of 4'-dimethylaminoflavylum, we have also performed reverse pH jump experiments on either pseudo- or thermodynamically equilibrated solutions at pH 10.5.

Pseudoequilibrated solutions at pH 10.5 were back-acidified to pH values between 1.5 and 5.0. Figure 11 a and b shows the spectral changes registered by stopped-flow equipment as a function of time (within 20 s) on a solution reacidified to pH 4.1.

The results obtained show that (i) 20 s after the pH jump, the only species present is the 4'-dimethylaminoflavylum ion (AH^+); (ii) the absorption spectrum immediately after the mixing time is slightly different from that of the starting (Cc^-) spectrum; (iii) the formation of the AH^+ form (monitored at 535 nm)

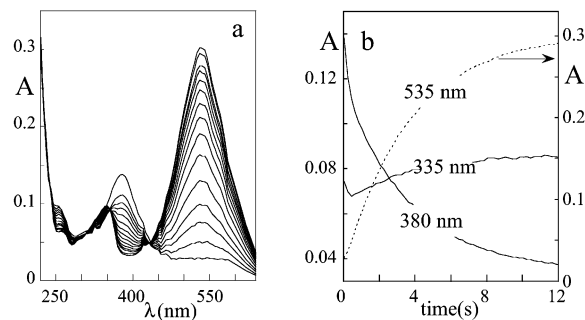


Figure 11. Spectral changes obtained by stopped-flow measurements upon a pH jump from freshly prepared solutions at pH 10.5 (Cc^-) to 4.1: (a) spectral changes obtained within 20 s; (b) spectral changes observed at three different wavelengths.

Table 2. Observed First-Order Rate Constants for the Kinetic Processes Occurring upon a pH Jump from Freshly Prepared Solutions at pH 10.5 (Cc^-) to Acidic pH Values (pH < 7)^a

final pH	$k_{\text{obs}} \text{ (s}^{-1}\text{)}$	$k_{\text{obs}} \text{ (s}^{-1}\text{)}$
4.77	6.4	0.097
4.10	6.6	0.27
3.12	6.4	0.97
2.59	3.8	1.5
1.50	3.06	

^a Stopped-flow measurements.

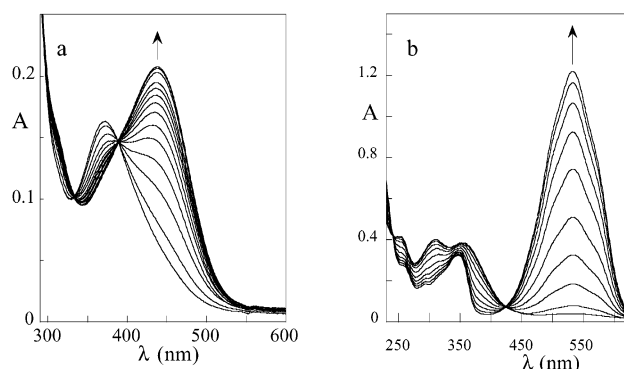


Figure 12. Spectral changes obtained upon continuous irradiation at 365 nm of solutions of 4'-dimethylaminoflavylum: (a) pH 11.2 (irradiation of the Cc^- form); (b) pH 1.2 (irradiation of the Ct^+ form).

follows a first-order kinetic with $k = 0.27 \text{ s}^{-1}$; (iv) when the process is monitored at 335 or 380 nm, two consecutive first-order processes are observed, whose rate constants are reported in Table 2; (v) the rate of the first process is scarcely affected by pH; and (vi) the second process is pH dependent, and its rate constant is essentially the same as that of the only process that is revealed by monitoring the reaction at 535 nm.

These results can be rationalized on the basis of the scheme shown in Figure 7. According to the scheme, the pH jump from pH 10.7 to pH 4.1 converts Cc^- into **Cc**. This simple protonation step, which is expected to be very fast, can be responsible for the spectral changes observed within the dead time of the stopped-flow apparatus. The second step, which is almost pH independent and ends within 0.5 s, can be associated with the tautomerization reaction that converts **Cc** into **B2**. The third, pH-dependent step, which is the only one seen when the reaction is monitored at 535 nm, is identified as the dehydration reaction that leads to the formation of AH^+ . The small decrease of the rate constant of the fast process can be due to the involvement of Cc^+ instead of **Cc** in the tautomeric process at low pH values.

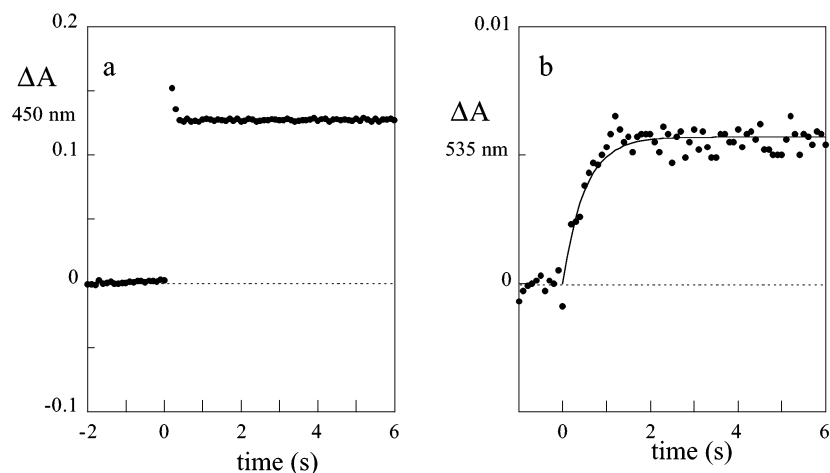


Figure 13. Absorbance changes obtained upon pulsed irradiation with white light of solutions of 4'-dimethylaminoflavylum: (a) Pseudoequilibrated solutions at pH 11.2 (irradiation of the Cc^- form); (b) equilibrated solutions at pH 1.2 (irradiation of the Ct^+ form).

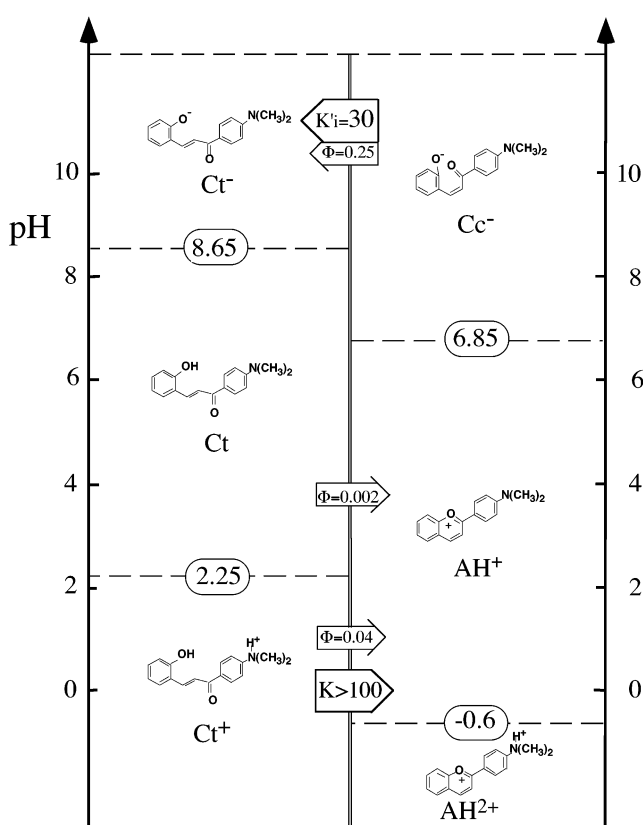


Figure 14. Scheme showing the thermal and photochemical behavior of 4'-dimethylaminoflavylum as a function of pH.

Photochemical Experiments. Continuous Irradiation. No spectral variation was observed upon 1 h irradiation of solutions of 4'-dimethylaminoflavylum ion at pH 1.0 with 365–600 nm light, showing that AH^+ is photochemically inert.

Continuous irradiation with 365 nm light of pseudoequilibrated solutions at pH 11.2, which, as we have seen, contain only the Cc^- form, causes the same spectral changes as those observed, at the same pH, for the thermal reaction that in a few days at room temperature (or in 17 h at 60 °C) leads to the Ct^- species (Figure 12a). The photoreaction seems to go to completeness because no AH^+ was observed upon reacidification to pH 1. The quantum yield of the $Cc^- \rightarrow Ct^-$ photoisomerization is 0.25. These results indicate that Ct^- is practically

photochemically inert (otherwise a photostationary state would have been reached).

The photochemical inertness of Ct^- is confirmed by the lack of spectral changes in a solution of Ct^- at pH 11.2 irradiated at 435 nm for 2 h. Solutions of photochemically obtained Ct^- at pH 11.2 have been submitted to pH jumps toward the acidic region (pH 3.7 and 1.2) and then have been irradiated with 365 nm light. To avoid precipitation of the sparingly soluble neutral Ct form, 10% of acetonitrile was added to the solution.

The spectral changes exhibited by the solution at pH 3.7 are in agreement with the formation of the AH^+ species. The quantum yield for this photoconversion is 2×10^{-3} . The spectral changes exhibited by the solution at pH 1.2 upon irradiation at 365 nm (Figure 12b) show that also the Ct^+ form is completely converted, with quantum yield 0.04, into the AH^+ species.

Flash Photolysis. As pointed out in previous papers,^{12,16,17} flash photolysis experiments can be most useful to confirm and/or complement the results obtained by the pH jump measurements.

Pseudoequilibrated solutions at pH 11.2 containing Cc^- were irradiated with a flash lamp (pulse width ca. 0.1 s), and the changes in absorbance were monitored as a function of time. The trace obtained (Figure 13a) at 450 nm, which is the absorption maximum of Ct^- , shows that the spectral changes occur within the time of the flash (the absorbance increases and then remains constant).

Flash photolysis of solutions at pH 1.2, where the compound is present in the Ct^+ form, has also been performed. The changes in absorbance at 535 nm (maximum of the AH^+ species) are reported in Figure 13b. The results show that, in this case, AH^+ is not formed during the flash, but via a first-order process, with a rate constant of 2 s^{-1} . This value is similar to the one reported in Table 2 for the reverse pH jump from a nonequilibrated solution at pH 10.5 to pH 1.5. Although the pH is slightly different (1.2 vs 1.5), the similarity between the rate constant values suggests we are dealing with the same processes. In fact, both experiments, the reverse pH jump of a nonequilibrated solution to pH 1.5 and the flash irradiation of Ct^+ at pH 1.2, lead to Cc that converts into AH^+ through $B2$.

Write–Lock–Read–Unlock–Erase Cycle. The results concerning the thermal and photochemical stability of the various forms of 4'-dimethylaminoflavylum are schematically summarized in Figure 14. This scheme shows the interplay

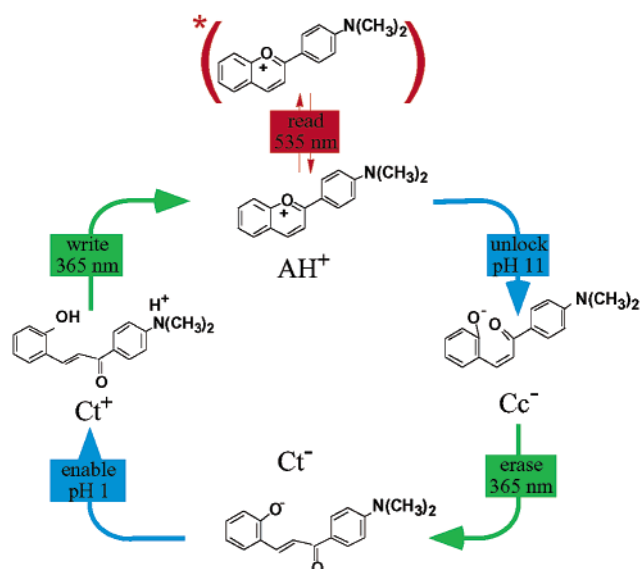


Figure 15. Example of the write–lock–read–unlock–erase cycle based on the 4′-dimethylaminoflavylium compound.

between pH and light stimulation in controlling the behavior of the system.

By combining these two types of stimuli, we found that the system can perform a write–lock–read–unlock–erase cycle, as illustrated in Figure 15. Starting with the species Ct^+ at pH 1.0, writing can be performed by light excitation which results in the formation of AH^+ , with a pale-yellow to intense-red change in color.

The signal monitoring the writing step is strong, and it can be read without interferences. Because AH^+ is photostable, the written information is autolocked. The unlock step can then be performed through a pH jump to the basic region, with formation of Cc^- , which can then be photochemically converted (erasing) to Ct^- . The system can be stored in this form. Before beginning a new cycle, the system has to be enabled by a jump to pH 1.0.

Conclusions

In all of the synthetic flavylium salts whose photochemistry had been previously reported, the photoreactive species is the Ct form, and the photoreaction leads to the AH^+ species, accompanied by an increase in the pH of the solution. In the case of 4′-dimethylaminoflavylium, the writing photoreaction converts Ct^+ into AH^+ (Figure 15), without any pH change. The effect is not significant because the system is studied in solution at pH 1.0 or 2.0, but it could be a useful property if solid-state devices are considered.

Experimental Section

4′-Dimethylaminoflavylium tetrafluoroborate was prepared²⁷ from condensation of 4′-dimethylaminoacetophenone and 2-hydroxybenzaldehyde in the presence of tetrafluoroboric acid (21%); mp 216–220 °C. ¹H NMR (400 MHz, D₂O, pD 1): δ 2.59 (s, 6H, N(CH₃)₂), 6.08 (d, *J* = 9.24 Hz, 2H, H_{3′+5′}), 7.13–7.17 (m, 2H, H₆ or H₇ + H₅ or H₈), 7.28–7.31 (m, 2H, H₃ + H₅ or H₈), 7.36 (2, *J* = 9.22, 2H, H_{2′6′}), 7.42 (t, *J* = 7.54 Hz, 1H, H₆ or H₇), 7.79 (d, *J* = 9.30 Hz, 1H, H₄).

All other chemicals were of analytical grade. The experiments were carried out in water. The pH of the aqueous solutions was adjusted by addition of HCl, or buffer, and was measured in a Metrohm 713 pH meter.³³

Spectra were recorded on a Perkin-Elmer Lambda 6 spectrophotometer, with temperature controlled by a thermostated water bath Selecta Frigitem 6000382.

Light excitation was carried out using a medium-pressure mercury arc lamp, and the irradiation wavelength was isolated with interference filters (Oriol). The intensity of the incident light was measured with a ferrioxalate actinometer.³⁴

The ¹H NMR spectra in deuterated water were obtained on a Bruker ARX-400 spectrometer operating at 400.13 MHz.³⁵

Reaction kinetic profiles were collected on the SX 18 MV stopped-flow (Applied Photophysics) spectrophotometer interfaced to a computer for data collection and analysis. The kinetic absorbance curve was recorded and evaluated with the ProK program of kinetic analysis. The standard flow tube has an observation path length of 1 cm. The driving ram for the mixing system was operated to the recommended pressure of 8.5 bar. Under these conditions, the time required to fill the 1 cm observation cell was experimentally determined to be 1.35 ms (based on a test reaction). For all kinetic measurements, the cell block and drive syringes were thermostated at 293 K using a circulating constant-temperature bath.

Crystal Structure of 4-Aminoflavylium. A dark orange prism crystal of C₁₅H₁₂F₆NOP (367.23), crystal size 0.56 × 0.24 × 0.04 mm³, crystallized from acetic acid/acetonitrile/water, was used for the structure determination. The chosen crystal was mounted on a glass fiber using an epoxy resin. Data were collected by means of an Enraf Nonius TurboCAD4. Cell parameters were refined from the setting angles of 25 reflections (*q* range 4.07–72.03). Reflections were measured from the nonprofiled ω/2*q* scans method. Of the 3199 reflections measured, all of which were collected for Lorentz and polarization effects and for absorption (maximum and minimum transmission coefficients of 0.8078 and 0.7193), 3035 [*R*(int) = 0.0571] independent reflections exceeded the significance level *F*/*σ*(*F*) > 2.0. The structure was solved by direct methods and refined by full-matrix least-squares methods on *F*². Refinement converged at a final *R*1 = 0.0931, *wR*2 = 0.2613 [*I* > 2*σ*(*I*)]. Minimum and maximum final electron density −0.410 and 0.4471 e Å^{−3}.

The computing structure solution was taken from SIR97,^{36a} the computing structure refinement was from SHELXL-97,^{36b} the computing molecular graphics were from Ortep-3^{37a} for Windows, and the computing publication material was from WinGX publication routines.^{37b} A summary of the experimental and structure solution procedure is given in the Supporting Information.

Acknowledgment. This work was supported by Fundação para a Ciência e Tecnologia project 32442/99 (Portugal), PRAXIS/QUI/10137/98, HPRN-CT-2000-29 (EC). A.R. thanks support from grant PRAXIS XXI/BD 13330/97. Financial support from MURST and CNR (Italy) is also acknowledged.

Supporting Information Available: X-ray data for the 4′-aminoflavylium compound (PF₆[−] salt) (PDF). This material is available free of charge via the Internet at <http://pubs.acs.org>.

JA0287276

- (33) The negative logarithm of the analytical concentration of the acid was used for pH values lower than 1.
- (34) Hatchard, C. G.; Parker, C. A. *Proc. R. Soc. London, Ser. A* **1956**, 235, 518.
- (35) Quoted pH values are direct meter readings without correction for the isotopic effect: Glasoe, P. K.; Long, F. A. *J. Phys. Chem.* **1960**, 64, 188.
- (36) (a) Altomare, A.; Cascarano, G.; Giacovazzo, G.; Guagliardi, A.; Moliterni, A. G. *SIR97: Direct Method Program for the Resolution and Refinement of Crystal Structures Using Single-Crystal Data*; 1997. (b) SHELXL, *An Integrated System for Solving and Refining Crystal Structures from Diffraction Data [Revision 5.1.]*; Bruker AXS Ltd.
- (37) (a) Farrugia, L. J. *J. Appl. Crystallogr.* **1997**, 30, 565. (b) Farrugia, L. J. *J. Appl. Crystallogr.* **1999**, 32, 837–838.