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A solvatochromic study of new benzo[a]phenothiazines for the determination of dipole moments and specific solute–solvent interactions in the first excited singlet state [1]

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Abstract

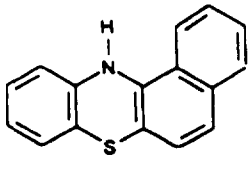
The electronic absorption and fluorescence excitation and emission spectra of seven benzo[a]phenothiazines, including 12H-benzo[a]phenothiazine, 9-methyl-benzo[a]phenothiazine, 10-methyl-benzo[a]phenothiazine, 11-methyl-benzo[a]phenothiazine, 5-oxo-5H-benzo[a]phenothiazine, 5-oxo-6-methyl-benzo[a]phenothiazine and 5-oxo-6-hydroxy-benzo[a]phenothiazine, were determined at room temperature (298 K) in solvents of various polarity (cyclohexane, ethyl ether, ethyl acetate, tetrahydrofuran, ethanol, dimethylformamide, acetonitrile and dimethylsulphoxide). The effect of the solvent on the spectral characteristics was studied quantitatively. In combination with the ground state dipole moments of these compounds, the spectral data of the benzo[a]phenothiazines were used to evaluate their first excited singlet state dipole moments using the solvatochromic shift method (Bakhshiev and Kawski–Chamma–Viallet correlations). The theoretical ground and excited singlet state dipole moments of the benzo[a]phenothiazines were also calculated as the vector sum of the π component (obtained by the Pariser–Parr–Pople method) and the σ component (obtained from σ bond moments). In most cases, a satisfactory agreement was found between the experimental and calculated values of the dipole moments. For most benzo[a]phenothiazine derivatives under study, the experimental excited singlet state dipole moments were higher than their ground state counterparts. The application of the Kamlet–Abboud–Taft solvatochromic parameters to explain the effect of the solvent on the spectral properties of benzo[a]phenothiazines is discussed.

Keywords: Benzo[a]phenothiazines; Dipole moments; First excited singlet state; Solute–solvent interactions; Solvatochromic study

1. Introduction

Phenothiazine and many of its derivatives, having a variety of structural and electronic properties, are used for various important applications [1–5]. Some of these heterocycles, such as prometazine, chlorpromazine and trifluoropromazine, are employed as psychotropic, sedative and antidepressant drugs [1,2]. In addition, methylene blue, methylene violet and methylene green have been investigated for their photochemotherapeutic action against carcinomas [3]. Phenothiazine derivatives have also been used as insecticides, dyes, pigments and acid–base indicators [4,5].

Recently, a family of these heterocycles, including the benzo[a]-, benzo[b]- and benzo[c]phenothiazines and their derivatives, have been synthesized in several ways [6–9]; they have received considerable attention due to their electronic and therapeutic properties [10–17]. The structure of benzo[a]phenothiazine is shown below.



Owing to their quinone-like structure, benzophenothiazines are strongly coloured ($\lambda > 450$ nm), and are generally utilized as polycyclic dyes [10] or pigments for synthetic

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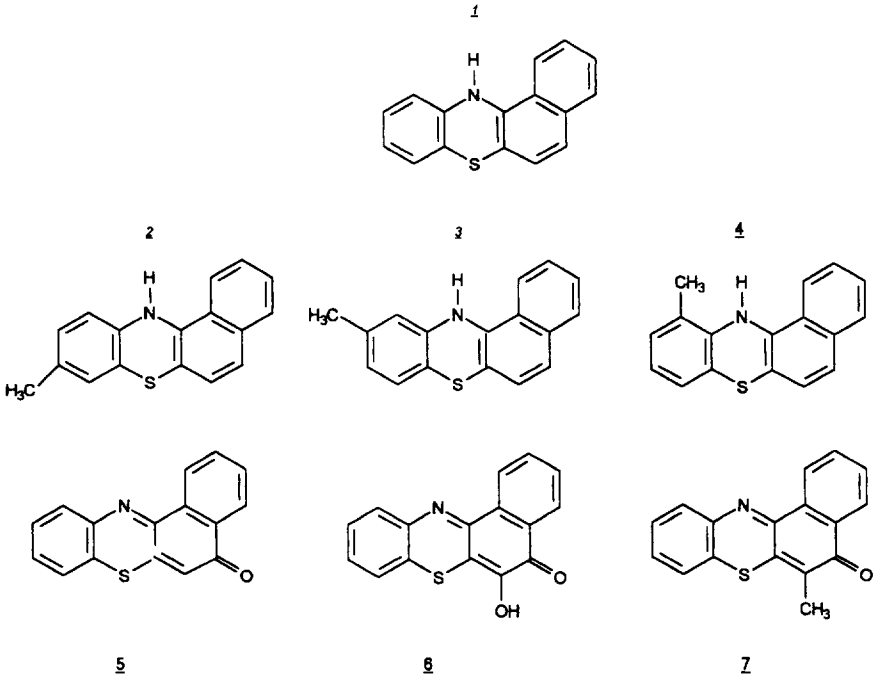


Fig. 1. Structures of benzo[a]phenothiazine derivatives.

polymers [11] and in optical recording media [12]. Some of the benzo[a]- and benzo[c]phenothiazine derivatives are potential anthelminthics [13] and possess antiviral activity, inhibiting the multiplication of encephalomyocarditis, Ranikhet disease and New Castle disease viruses in tissue cultures [14]. Other benzo[a]phenothiazines and their hydro derivatives are strong leukotriene inhibitors, useful in pharmaceuticals for the treatment of allergic, inflammatory and cardiovascular diseases [15]. Relationships between the antitumour activity of benzo[a]phenothiazines and their π electron density, calculated by the Hückel and MNDO orbital methods, were established by Motohashi et al. [17].

The photophysical and photochemical properties of several benzophenothiazines have also been widely studied [10,18–23]. Some of these derivatives were investigated as a group of photosensitizers acting in vitro, via an electron transfer mechanism [18–20]. Other investigations [10] have been devoted to tautomerism recognition of quinone imine benzophenothiazines on the basis of visible absorption spectral data. Barra et al. [21] have studied the photochemistry of benzo[c]phenothiazine in polymethacrylate polymers using time-resolved laser techniques. These researchers have demonstrated that the luminescence properties of this compound are similar in polymer matrices and in solution. They also found that benzo[c]phenothiazine exhibits a long-lived triplet–triplet absorption. In spite of this important research effort on benzophenothiazines, the solvent-dependent properties have not been investigated with the exception of our preliminary studies [22,23].

The goal of this work is to report the influence of solvents of various polarity on the electronic absorption and fluorescence spectra of seven selected benzo[a]phenothiazine derivatives (see structures in Fig. 1), and the evaluation of their dipole moments in the excited singlet state using the Bakhshiev and Kawski–Chamma–Viallet solvatochromic methods. In addition, the experimental ground and excited singlet state dipole moments are compared with the theoretical values calculated using a combination of the Pariser–Parr–Pople (PPP) method (π component) and the σ bond contribution (σ component). Finally, in order to evaluate the contribution of the different types of solute–solvent interaction in the excited state, the Kamlet–Abboud–Taft equation is applied to our spectral data.

2. Experimental details

2.1. Chemicals

12H-Benzo[a]phenothiazine (**1**), 9-methyl-12H-benzo[a]phenothiazine (**2**), 10-methyl-12H-benzo[a]phenothiazine (**3**), 11-methyl-12H-benzo[a]phenothiazine (**4**), 5-oxo-5H-benzo[a]phenothiazine (**5**), 6-hydroxy-5-oxo-5H-benzo[a]phenothiazine (**6**) and 6-methyl-5-oxo-5H-benzo[a]phenothiazine (**7**) were synthesized [16,17]. Aldrich and Merck analytical or spectroscopic grade solvents (cyclohexane, ethyl ether, ethyl acetate, tetrahydrofuran (THF), ethanol, dimethylformamide (DMF), acetonitrile and dimethylsulphoxide (DMSO)) were used to prepare the solutions.

2.2. Spectral measurements

UV–visible absorption spectra were determined at room temperature (298 K) on a Varian DMS 200 spectrophotom-

eter. Fluorescence spectra were recorded at room temperature using a Perkin–Elmer LS-5 spectrophotofluorometer.

2.3. Dipole moment measurements

The ground state dipole moments were measured in dioxan at 293 K using a dipole meter DM-01 (Wissenschaftlich-Technische Werkstätten, Weilheim, Germany) equipped with a DFL-2 cell as described previously [22,24–27]. The calibration of the instrument was carried out with six solvents of different polarity ranging from *n*-hexane to *n*-butyl ether.

Two formulae were used to determine the excited singlet state dipole moments by the solvatochromic method.

Bakhshiev's formula [28]

$$\tilde{\nu}_A - \tilde{\nu}_F = \frac{2(\vec{\mu}_e - \vec{\mu}_g)^2}{hca_0^3} F_1 \quad (1)$$

where $\tilde{\nu}_A$ and $\tilde{\nu}_F$ are the wavenumbers (cm^{-1}) of the absorption and emission maxima respectively, $\vec{\mu}_g$ is the permanent dipole moment in the ground state, $\vec{\mu}_e$ is the permanent dipole moment in the excited singlet state, a_0 is the Onsager cavity radius and F_1 is defined as follows (solvent polarity function)

$$F_1 = \left[\frac{D-1}{D+2} - \frac{n^2-1}{n^2+2}\right]\frac{2n^2+1}{n^2+2} \quad (2)$$

where D is the solvent dielectric constant and n is the solvent refractive index.

Kawski–Chamma–Viallet's formula [29,30]

$$\frac{\tilde{\nu}_A + \tilde{\nu}_F}{2} = \frac{2(\mu_e^2 - \mu_g^2)}{hca_0^3} F_2 \quad (3)$$

where the meaning of the symbols is the same as in Eqs. (1) and (2), except for F_2 which is defined as follows

$$F_2 = \frac{2n^2+1}{2(n^2+2)}\left[\frac{D-1}{D+2} - \frac{n^2-1}{n^2+2}\right] + \frac{3(n^4-1)}{2(n^2+2)^2} \quad (4)$$

The value of the solute cavity radius (a_0) was calculated from the molecular volume of the benzo[a]phenothiazine derivatives according to Suppan's equation [31]

$$a_0 = \left[\frac{3M}{4\pi dN}\right]^{1/3} \quad (5)$$

where M is the molecular weight of the solute, d is the density of the solute molecule and N is Avogadro's number. The solid state densities of the derivatives were determined pycnometrically at 295 K in the form of a suspension of the respective compound (600–1200 mg) in kerosene. The results are summarized in Table 1.

2.4. Theoretical ground and excited singlet state dipole moments

A combination of the PPP (π-LCI-SFC-MO) method [32,33] and the σ bond contribution was used to calculate the theoretical total ground state dipole moment ($\mu_{g,t}$) as the vector sum of the respective π and σ components, μ_π and μ_σ. All calculations were carried out on a Hewlett-Packard HP 150 II touchscreen computer with an 8087 coprocessor. The parametrization was similar to that employed in previous studies [22–27]; the Mataga–Nishimoto formula was used for the calculation of the bicentric electronic repulsion integrals ($\gamma_{\mu\nu}$) [34]

$$\gamma_{\mu\nu} = \frac{14.399}{l_{\mu\nu} + 1.328\ \text{eV}} \quad (6)$$

where $l_{\mu\nu}$ (Å) is the distance between atom μ and atom ν.

The excited singlet state dipole moments were computed using a combination of the PPP method and the empirical σ bond contribution. In the case of the π contribution, it was assumed that the $1 \rightarrow 1'$(HOMO $\rightarrow$ LUMO) π,π^* transition was the most important, while the σ contribution was assumed to remain the same in the excited state as in the ground state.

Table 1
Solid state densities (d^{22}) and solute cavity radii (a_0) of benzo[a]phenothiazines

Number	Compound	Solid state density d^{22}[a]	a_0 (Å)[b]
1	12H-BZPHT	1.365	4.16
2	9-Me-BZPHT	1.365	4.24
3	10-Me-BZPHT	1.365	4.24
4	11-Me-BZPHT	1.365	4.24
5	5-Oxo-BZPHT	1.365	4.24
6	5-Oxo-6-OH-BZPHT	1.365	4.33
7	5-Oxo-6-OH-BZPHT	1.365	4.32

[a]Determined pycnometrically for benzo[a]phenothiazine and estimated in the same way for the remaining compounds.
[b]The solute cavity radii were calculated according to the Suppan equation (Eq. (5)).

3. Results and discussion

3.1. Solvent effects on the absorption and fluorescence spectra

The electronic absorption and fluorescence excitation and emission spectra of the benzo[a]phenothiazine derivatives were investigated in several solvents of different polarity and hydrogen bonding ability. The spectral properties are summarized in Table 2.

All the electronic absorption spectra present two main bands. The absorption maxima of unsubstituted and methyl-substituted benzo[a]phenothiazine derivatives (**1–4**) are located in the 220–280 nm and 320–350 nm regions, whereas the maxima of the oxo derivatives (**5–7**) appear at about 240–320 nm and 360–700 nm. The shortest wavelength bands with high molar absorption coefficients ($\log \varepsilon = 4.7$–3.9) are attributed to the π,π^* (^1B) transitions. The long-wavelength bands, generally characterized by smaller molar absorption

Table 2
Absorption and fluorescence spectral properties of benzo[a]phenothiazine derivatives in solvents of different polarity[a]

Number	Compound	Solvent[b]	Absorption maxima λ_A (nm) (log ε)[c]	Fluorescence excitation maxima λ_{ex} (nm)[d]	Fluorescence emission maxima λ_{em} (nm)[d]
1	12H-BZPHT	Cyclohexane	219(4.63), (246)(4.49), (258)(4.43), 275(4.76)	(248), 274, 352	474, (501)
		Ethyl ether	215(4.79), (258)(4.21), 275(5.01)	255, 275, 335	489, (510)
		Ethyl acetate	232(4.80), (251)(4.51), 273(4.79), (298)(4.11)	273, 335, (384)	496, (513)
		THF	237(3.70), 256(3.62), 272(3.74), 282(3.58)	NF[e]	NF
		Ethanol	206(5.81), 255(5.66), 276(5.78), 325(5.08)	243, 268, 297	499, (516)
		DMF	222(5.15), 229(5.17), 276(4.98)	279, 340, (382)	508
		Acetonitrile	218(5.47), 255(5.22), 272(5.31), (325)(4.11)	264, 279, 339	509
		DMSO	250(4.32), 277(4.48)	268, 329	514
2	9-Me-BZPHT	Cyclohexane	257(4.38), 275(4.50), 335(3.65)	257, 276, 336, (384)	481, (503)
		Ethyl ether	259(4.50), 274(4.58), 338(3.79)	259, 273, 339, (383)	489, (510)
		Ethyl acetate	259(4.36), 274(4.43), 335(3.67)	267, 274, 340, (382)	(427), 504
		THF	238(4.54), 260(4.56), 276(4.64), 340(3.87)	280, 340, (382)	504
		Ethanol	258(4.43), 274(4.49), 335(3.71)	262, 275, 340, (383)	507
		DMF	(270)(4.50), 276(4.55), 335(3.79)	281, 341, (383)	516
		Acetonitrile	258(4.46), 272(4.50), 332(3.74)	272, 340, (383)	516
		DMSO	260(4.48), 278(4.56), 336(3.84)	282, 342, (382)	520
3	10-Me-BZPHT	Cyclohexane	254(4.30), 277(4.52), 330(3.56)	277, 335, (382)	474, (501)
		Ethyl ether	256(4.35), 277(4.51), 335(3.59)	(257), 277, 339, (385)	492, (506)
		Ethyl acetate	256(4.49), 276(4.68), 342(3.68)	268, 277, 339, (380)	502
		THF	239(4.29), 257(4.29), 278(4.46), 335(3.58)	280, 340, (380)	502
		Ethanol	257(4.43), 276(4.57), 338(3.67)	263, 277, 340, (380)	506
		DMF	268(4.48), 278(4.58), 335(3.72)	283, 343, (382)	514
		Acetonitrile	(258)(4.41), 275(4.54), 336(3.67)	272, 341, (384)	514
		DMSO	(259)(4.31), 279(4.51), 351(3.60)	282, 343, (380)	519
4	11-Me-BZPHT	Cyclohexane	(259)(4.28), 275(4.46)	261, 273, (317), (381)	500
		Ethyl ether	(260)(4.31), 274(4.44)	261, 273, (321), (380)	489, (504)
		Ethyl acetate	(260)(4.31), 274(4.44)	(268), 273, (325), (379)	500
		THF	235(3.97), (260)(4.0), 275(4.14)	(268), 277, 329, (383)	499
		Ethanol	(260)(4.31), 274(4.44)	262, 273, (321), (380)	500
		DMF	(257)(4.32), (268)(4.57), 274(4.64)	280, 324, (385)	510
		Acetonitrile	(260)(4.33), 272(4.38)	271, (333), (382)	511
		DMSO	(260)(4.31), 276(4.43)	280, 326, (341), (383)	515
5	5-Oxo-BZPHT	Cyclohexane	258(4.07), 308(3.93), 360(3.74), 377(3.69), 456(3.66)	(248), 274, 352	474, (501)

(continued)

Table 2 (*continued*)

Number	Compound	Solvent[b]	Absorption maxima λ_A (nm) (log ε)[c]	Fluorescence excitation maxima λ_{ex} (nm)[d]	Fluorescence emission maxima λ_{em} (nm)[d]
		Ethyl ether	233(4.19), 257(4.21), 308(4.02), 379(3.81), 460(3.77)	277, 346, (377)	493, (507)
		Ethyl acetate	256(4.12), 308(3.94), 362(3.73), 469(3.66)	277, 343, (381)	506
		THF	238(4.17), 258(4.20), 312(4.01), 364(3.83), 468(3.76)	280, 344, (381)	506
		Ethanol	255(4.22), 309(4.02), 369(3.80), 476(3.79)	277, 346, (377)	517
		DMF	266(4.45), 311(4.36), 369(4.18), 475(4.08)	282, 351, (379)	520
		Acetonitrile	257(4.41), 308(4.12), 365(3.89), 470(3.85)	275, 355, (380)	524
		DMSO	260(4.33), 313(4.14), 371(3.93), 478(3.89)	283, 353, (378)	524
6	5-Oxo-6-OH-BZPHT	Cyclohexane	253(3.92), 267(4.17), 473(3.41), 534(3.52), 699(3.31)	NF[e]	NF
		Ethyl ether	252(4.51), 266(4.47), 322(4.15), 357(4.15), 517(4.02)	NF	NF
		Ethyl acetate	252(4.51), 266(4.48), 322(4.22), 356(4.22), 515(4.08)	NF	NF
		THF	254(4.52), 266(4.49), 326(4.07), 359(4.08), 522(3.90)	NF	NF
		Ethanol	252(4.17), 267(4.12), 325(3.86), 359(3.88), 523(3.74)	NF	NF
		DMF	253(3.92), 267(4.17), 473(3.41), 534(3.52), 699(3.34)	NF	NF
		Acetonitrile	253(4.46), (267)(4.44), 322(4.97), 354(3.95), 516(3.80)	NF	NF
		DMSO	259(4.17), 267(4.12), 325(3.86), 359(3.88), 523(3.74)	NF	NF
7	5-Oxo-6-Me-BZPHT	Cyclohexane	253(4.35), 261(4.33), 285(4.09), 311(4.24), 375(3.98), 465(3.97)	NF[e]	NF
		Ethyl ether	254(4.05), 284(3.77), 312(3.91), 359(3.72), 376(3.67), 464(3.68)	NF	NF
		Ethyl acetate	254(4.19), 309(4.03), 359(3.82), 376(3.78), 468(3.79)	NF	NF
		THF	254(4.16), 314(4.01), 359(3.80), 379(3.89), 469(3.77)	NF	NF
		Ethanol	253(4.03), 307(3.84), 383(3.60), 473(3.62)	NF	NF
		DMF	269(3.82), 313(3.81), 367(3.60), 475(3.59)		
		Acetonitrile	254(4.09), 307(3.93), 360(3.68), 468(3.69)	NF	NF
		DMSO	258(3.92), 315(3.75), 369(3.52), 478(3.51)	NF	NF

[a]The concentrations of benzo[a]phenothiazine derivatives were 10^{-5} M for the absorption spectra and 10^{-6} M for the fluorescence spectra.
[b]Solvents are listed in order of increasing dielectric constant.
[c]The underlined wavelengths and the wavelengths in parentheses correspond to maxima and shoulders respectively. The logarithm of the molar absorption coefficient (ε in M^{-1} cm^{-1}) is given in parentheses. Wavelength precision, ± 1 nm.
[d]Wavelength precision, ± 1 nm.
[e]NF, not fluorescent in this solvent.

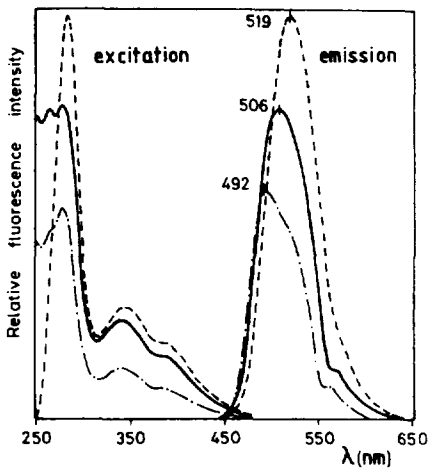


Fig. 2. Solvent effect on the fluorescence excitation and emission spectra of 10^{-6} M 10-methyl-12H-benzo[a]phenothiazine. Solvents: ethyl ether (- · -), ethanol (———) and DMSO (– – –).

coefficients ($\log \varepsilon = 4.0$–3.3), are attributed to the π,π^* (^1L_a and ^1L_b) transitions (Table 2). The absorption spectra of the methyl-benzo[a]phenothiazine derivatives are very similar to those of unsubstituted phenothiazine and its derivatives [35]. In contrast, the spectra of the oxo derivatives are strongly red shifted by about 200 nm. The latter feature indicates a much more stabilized electronic structure for these compounds, resulting from their quinone-like electronic distribution [22]. On varying the solvent polarity, relatively small shifts in the absorption maxima are observed, ranging from 2–7 nm for the first bands to 4–22 nm for the second.

With the exception of compounds **6** and **7**, the benzo[a]phenothiazines exhibit a rather strong native fluorescence; for most compounds, the fluorescence excitation spectra contain three bands and, in some cases, a shoulder located at a longer wavelength (about 380 nm). The excitation wavelengths are generally very close to the absorption wavelengths. The fluorescence emission spectra of the benzo[a]phenothiazine derivatives show only one peak at 470–525 nm (Fig. 2). In the case of the less polar solvents, a shoulder is generally located at longer wavelengths. The fluorescence maxima of the benzo[a]phenothiazines are significantly red shifted, by about 26–70 nm, relative to the emission maxima of unsubstituted phenothiazine and some of its derivatives [35]. On increasing the solvent polarity from cyclohexane to DMSO, the fluorescence emission maxima are red shifted by at least 40 nm. An exception is compound **4**, for which the emission spectra are red shifted by only about 16 nm (Table 2). Such shifts can be attributed to the occurrence of a π^*,π deactivation transition of the fluorophore.

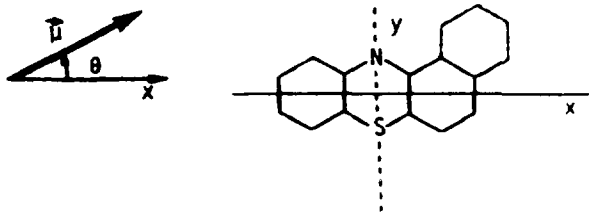
3.2. Experimental and calculated ground state dipole moments

In Table 3 we report, for the seven compounds under study, the theoretical ground state dipole moments, obtained as the vector sum of the π contribution (PPP method) and the σ contribution (σ bond moments). The direction of the calculated total dipole moments is also shown.

Table 3
Comparison of the experimental and calculated ground state dipole moments (D)[a]

Number	Compound	Dipole moment μ_g (D)			
		Calculated	θ_t(°)[b]	Experimental	E (%)[c]
1	12H-BZPHT	2.65	−87	3.69	28.1
2	9-Me-BZPHT	2.60	−82	3.47	25.1
3	10-Me-BZPHT	2.72	−84	3.91	30.4
4	11-Me-BZPHT	2.73	−84	2.87	4.8
5	5-Oxo-BZPHT	4.99	−27	5.53	9.8
6	5-Oxo-6-OH-BZPHT	1.89	−53	5.39	64.9
7	5-Oxo-6-Me-BZPHT	4.47	−25	2.58	42.3

[a]Dipole moment measurements in dioxan at 293 K.
[b]Calculated angle between the positive direction of the x axis and the direction of the total calculated dipole moment read counterclockwise, for the orientation of the structure as shown below.
[c]E is the difference (in per cent) between the experimental and calculated dipole moments.



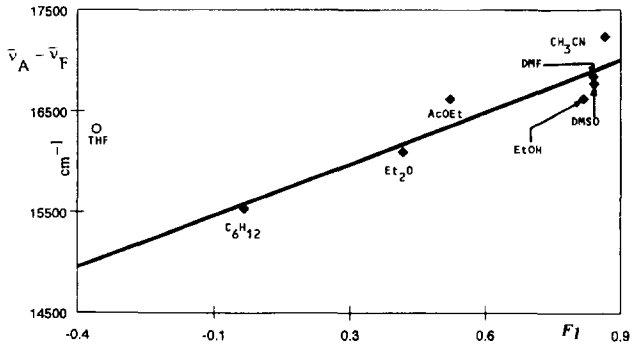


Fig. 3. Example of Bakhshiev correlation between the solvent spectral shifts and the F_1 solvent polarity function for 11-methyl-12H-benzo[a]-phenothiazine (**4**); ○, solvent which does not obey the correlation.

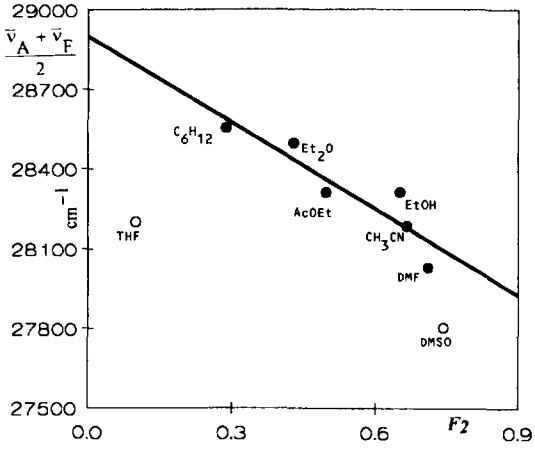


Fig. 4. Example of Kawski–Chamma–Viallet correlation between the solvent spectral shifts and the F_2 solvent polarity function for 11-methyl-12H-benzo[a]phenothiazine (**4**); ○, solvents which do not obey the correlation.

The experimental dipole moments of these compounds are compared with the calculated values (Table 3). In general, satisfactory agreement is found between the experimental and theoretical values. Indeed, the differences (E) between both sets of values range from 4% to 30%, depending on the compound, except for compounds **6** and **7** with E values of about 65% and 42% respectively.

The ground state dipole moments vary significantly with the nature of the substituent and, to a lesser extent, with its position on the benzo[a]phenothiazine ring. Indeed, when comparing the experimental values, it can be seen that the dipole moments of unsubstituted, 9- and 10-methyl derivatives are slightly larger ($\Delta\mu = 0.6$–1.1 D) than that of 11-Me-benzo[a]phenothiazine. In contrast, oxo-BZPHT derivatives (**5–7**) present significantly larger dipole moment values (approximately 2 D) than those obtained for the methyl-BZPHT derivatives, indicating stronger electronic interaction for the former structures. These results are in agreement with a less symmetric electronic distribution and the presence of possible dipolar resonance forms in the case of oxo-BZPHT derivatives [22].

3.3. Excited singlet state dipole moments

To determine the excited singlet state dipole moments of benzo[a]phenothiazines, we plotted the Stokes shifts ($\tilde{\nu}_A - \tilde{\nu}_F$) and ($\tilde{\nu}_A + \tilde{\nu}_F$)/2 against the solvent functions F_1 and F_2 respectively (see examples in Figs. 3 and 4). For all solvents, the wavenumbers ($\tilde{\nu}_A$) corresponding to the 258–269 nm and 272–280 nm absorption band maxima were used for the oxo derivatives (**5–7**) and benzo[a]phenothiazine and its methyl derivatives (**1–4**) respectively. The wavenumbers ($\tilde{\nu}_F$) of the long-wavelength fluorescence emission maxima (470–525 nm) for all benzo[a]phenothiazines were generally utilized in the correlations. The results of the statistical treatment of the Bakhshiev and Kawski–Chamma–Viallet correlations are satisfactory (Table 4). Indeed, with the exception of compounds **6** and **7**, which are not fluorescent, we found good linearity for both types of correlations (Figs. 3 and 4), with correlation coefficients larger than 0.91.

Table 4
Statistical treatment of the Bakhshiev and Kawski–Chamma–Viallet correlations of the solvent spectral shifts of benzo[a]phenothiazine derivatives

Number	Compound	Slope (cm^{-1})	Intercept (cm^{-1})	Correlation coefficient r	Number of data n
Bakhshiev correlation					
1	12H-BZPHT	1544	15488	0.926	6
2	9-Me-BZPHT	1631	15596	0.931	7
3	10-Me-BZPHT	1538	15334	0.947	7
4	11-Me-BZPHT	1574	15589	0.932	7
5	5-Oxo-BZPHT	786	19099	0.924	5
6	5-Oxo-6-OH-BZPHT[a]	–	–	–	–
7	5-Oxo-6-Me-BZPHT[a]	–	–	–	–
Kawski–Chamma–Viallet correlation					
1	12H-BZPHT	−1608	29129	0.940	7
2	9-Me-BZPHT	−1807	29620	0.947	7
3	10-Me-BZPHT	−1744	29680	0.931	7
4	11-Me-BZPHT	−1080	28901	0.912	6
5	5-Oxo-BZPHT	−2376	30630	0.938	5
6	5-Oxo-6-OH-BZPHT[a]	–	–	–	–
7	5-Oxo-6-Me-BZPHT[a]	–	–	–	–

[a]This compound is not fluorescent.

Table 5
Ground and first excited singlet state dipole moments of benzo[a]phenothiazines (D)

Number	Compound	μ_g (D)[a]		μ_{S1} (D)			
		Calculated	Experimental	Experimental I[b]	Experimental II[c]	Mean experimental (R.E. (%))[d]	Calculated[e] (E (%))
1	12H-BZPHT	2.65	3.69	7.0	5.0	6.0(33)	6.31(4.9)
2	9-Me-BZPHT	2.60	3.47	6.9	5.1	5.9(30)	6.99(15.6)
3	10-Me-BZPHT	2.72	3.91	7.4	5.3	6.4(33)	6.84(6.4)
4	11-Me-BZPHT	2.73	2.87	6.3	4.1	5.2(42)	6.56(20.7)
5	5-Oxo-BZPHT	4.99	5.53	7.9	6.9	7.5(13)	6.66(11.2)
6	5-Oxo-6-OH-BZPHT	1.89	5.39	NF[f]	–	–	6.12
7	5-Oxo-6-Me-BZPHT	4.47	2.58	NF[f]	–	–	6.67

[a]Experimental and calculated ground state dipole moments were taken from Table 3. Relative error between experimental and calculated values ranges from 1% to 26%.
[b]Experimental first excited singlet state dipole moments determined from Bakhshiev correlations.
[c]Experimental first excited singlet state dipole moments determined from Kawski–Chamma–Viallet correlations.
[d]Excited singlet state dipole moments (arithmetic mean values) (μ_{S1}) determined from I and II values. In parentheses, R.E. represents the relative error (in per cent) of μ_{S1} evaluated by the expression: $[(\mu_{S1}(I) - \mu_{S1}(II)) \times 100]/\bar{\mu}_{S1}$.
[e]Calculated first excited singlet state dipole moments. E is the difference (in per cent) between the calculated and mean experimental values of μ_{S1}. $E = [(\mu_{S1,calc} - \mu_{S1}) \times 100]/\mu_{S1}$.
[f]NF, not fluorescent.

For most compounds, the correlations are obeyed by at least five solvents. However, THF exhibits generally significant deviations from the correlations. These discrepancies are probably due to several types of specific solute–solvent interaction.

Table 5 shows the first excited singlet state dipole moments calculated and determined from the slopes of Bakhshiev and Kawski–Chamma–Viallet correlations, and their comparison with the ground state dipole moments. For all benzo[a]phenothiazine derivatives, relatively good agreement is observed between the excited singlet state dipole moments obtained from both types of correlations. The dipole moments obtained by the Bakhshiev correlation are, in all cases, approximately 2 D higher than those calculated by the Kawski–Chamma–Viallet correlation. This discrepancy may result from inherent calculation terms in both formulae. This has been observed previously for several series of compounds (i.e. phenothiazines [35], acridines [36] and coumarins [27]). Moreover, it can be seen that the dipole moments of the benzo[a]phenothiazines are significantly higher in the first excited singlet state than in the ground state. The difference is approximately 1.9–2.5 D.

In addition, it is interesting to stress that noticeable discrepancies occur between the experimental and theoretical values of the excited singlet state dipole moments for most compounds. These differences between experimental and calculated values may be due, in part, to the various assumptions and simplifications made in the use of Bakhshiev and Kawski–Chamma–Viallet correlations as discussed previously [25,26,37], and also to the strong specific effects of solvents of different nature occurring in the excited singlet state. In addition, the application of the PPP calculations to the excited state is subject to uncertainties, since the charge distribution of molecules in the excited state has not been fully elucidated [37].

In spite of these differences between the calculated and experimentally determined dipole moments, all the data support an enhancement of the dipole moment of benzo[a]phenothiazines in the excited singlet state relative to the ground state. This result indicates that these heterocycles are more polar in the excited singlet state than in the ground state. A similar conclusion was reached for unsubstituted phenothiazine and several of its derivatives [35]. Therefore this feature is a general property of phenothiazine and benzophenothiazine compounds.

3.4. Correlations with π^* and α solvatochromic parameters

In order to evaluate the respective contributions of the polarity/polarizability of the solvent and its hydrogen-bond-donor (HBD) ability in the ground and excited singlet state solute–solvent interactions of benzo[a]phenothiazine derivatives, we have applied a simplified form of the Kamlet–Abboud–Taft solvation energy relationship [38,39] to our electronic absorption and fluorescence data

$$XYZ = XYZ_0 + s\pi^* + a\alpha \quad (7)$$

where XYZ is a solvatochromic property, π^* is the solvent polarity/polarizability, α is the solvent HBD ability and s and a are the corresponding regression coefficients. Because of the insufficient number of data in non-hydrogen-bonding solvents, we have chosen the method of multiple linear regression analysis which is known to give results compara-

Table 6
Statistical treatment of the Kamlet–Abboud–Taft solvation energy relationships of the absorption and fluorescence spectral data of benzo[a]phenothiazines

Number	Compound	s^a (cm^{-1})	a^b (cm^{-1})	Intercept (cm^{-1})	Correlation coefficient r	Number of solvents n
Absorption spectral data						
1	12H-BZPHT	−241	−508	36394	0.981	5
2	9-Me-BZPHT	−63	253	36280	0.997	4
3	10-Me-BZPHT	−217	166	36172	0.962	5
4	11-Me-BZPHT	NC[c]	–	–	–	–
5	5-Oxo-BZPHT	−545	554	39081	0.957	5
6	5-Oxo-6-OH-BZPHT	−550	295	39734	0.900	4
7	5-Oxo-6-Me-BZPHT	−227	194	39490	0.900	4
Fluorescence spectral data						
1	12H-BZPHT	−1343	−185	20876	0.955	7
2	9-Me-BZPHT	−1541	−753	20722	0.996	8
3	10-Me-BZPHT	−1565	−253	20791	0.993	8
4	11-Me-BZPHT	−1416	−88	20802	0.938	8
5	5-Oxo-BZPHT	−1731	−598	20722	0.971	7

[a] s is the polarity/polarizability coefficient (see Eq. (7)).
[b] a is the HBD ability coefficient (see Eq. (7)).
[c] NC, no correlation.

ble with the stepwise method [38]. The π^* and α parameters taken from Ref. [38] were utilized. We used the wavenumbers of the absorption maxima ($\tilde{\nu}_A$) and fluorescence emission maxima ($\tilde{\nu}_F$) of the benzo[a]phenothiazines as described previously. The results of the statistical treatment of the Kamlet–Abboud–Taft correlations, i.e. the slopes, intercepts, standard deviations and correlation coefficients, are summarized in Table 6. The relationships indicate good linearity, as shown by the correlation coefficients larger than 0.90 for most compounds (Fig. 5). The majority of the solvents obey the correlations, with the exception of ethyl acetate, DMF and acetonitrile (in some cases). The number of solvents fitting the correlations is higher when using fluorescence energies than when using absorption energies (Table 6), which is probably due to the more pronounced solvent spectral shifts of the fluorescence maxima.

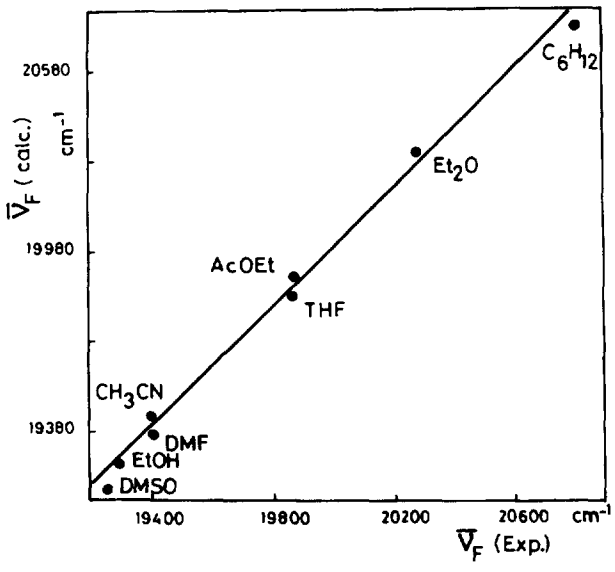


Fig. 5. Example of Kamlet–Abboud–Taft multiparameter solvation energy relationship for the fluorescence spectral data of 9-methyl-12H-benzo[a]phenothiazine.

The negative signs of the s coefficients indicate that increasing the solvent polarity/polarizability (π^*) leads to a shift in $\tilde{\nu}_A$ and $\tilde{\nu}_F$ bathochromically for all benzo[a]-phenothiazines (Table 6). This demonstrates that the excited singlet state of the benzo[a]phenothiazine derivatives becomes more stabilized when the solvent polarity increases. The above conclusion seems to be in agreement with the red-shifted spectra (Table 2) and also with the higher dipole moments of the benzo[a]phenothiazines in the excited singlet state.

In contrast, the a coefficients have negative values for fluorescence emission wavenumbers, whereas most of them are positive for the absorption data.

The positive a coefficients, found for the absorption spectral data correlations (except for compound **1**), indicate that increasing solvent HBD ability leads to a blue shift in $\tilde{\nu}_A$, and therefore to a decrease in the formation of solute–solvent hydrogen bonding in the excited singlet state relative to the ground state. Moreover, the HBD a coefficients vary with the structure of the benzo[a]phenothiazine derivatives. Indeed, they are slightly larger for the 5-oxo-BZPHT series, probably because of the presence of a carbonyl group (hydrogen-bonding acceptor).

It is also worth noting that, except in the case of the 5-oxo-BZPHT (**5**) derivative, the a coefficients are significantly smaller than the s coefficients for both absorption and fluorescence data. This demonstrates that the ability of the solvent to donate hydrogen bonds is much weaker than the solute–solvent dipole–dipole interactions occurring in the excited singlet state of most benzo[a]phenothiazine molecules.

4. Conclusions

The mathematical treatment of excited state solute–solvent electrostatic interactions (Bakhshiev and Kawski–Chamma–Viallet equations), applied here to the solvatochromic shifts of benzo[a]phenothiazine derivatives, has demonstrated that the dipole moments of these heterocycles are significantly larger in the excited singlet state than in the ground state. Although this electrostatic model is rather crude and allows the evaluation of only non-specific dipole–dipole interactions, it leads to a rather satisfactory agreement between the experimental and theoretical excited state dipole moments, as shown previously [22–27,35,36]. However, in order to take into account the role of specific solute–solvent associations in solvatochromic effects on benzo[a]phenothiazines, we used the Kamlet–Abboud–Taft equation. From the application of the latter approach, we can conclude that solute–solvent dipole–dipole interactions are considerably stronger than the formation of hydrogen bonds in the excited singlet state of most benzo[a]phenothiazines.

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