Heteroassociation of the bromine-containing anions of sulfophthaleins in aqueous solution

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The ability of bromine-containing anions of sulfophthalein dyes, such as bromophenol blue (BPB), bromocresol green (BCG), bromocresol purple (BCP), bromothymol blue (BTB), as well as non-substituted phenol red (PhR), to form heteroassociates in aqueous solution was investigated. Singly and doubly charged anions BPB, BCG, BCP, BTB, and PhR (HAn^-, An^{2-}) are capable of forming stable heteroassociates of composition $Ct^+ \cdot HAn^-$ and $(Ct^+)_2 \cdot An^{2-}$ with cationic polymethine dyes (Ct^+), such as pinacyanol and quinaldine red. The enthalpies of formation of the dye ions and heteroassociates were calculated by semiempirical methods, and the most probable structure of heteroassociates was determined.

Key words: sulfophthaleins, heteroassociation, spectrophotometry, aqueous solution, dye, constant of association, enthalpy of formation.

Sulfophthalein dyes have long been effectively used as acid-base and metallochromic indicators, and also as analytical reagents for photometric determination of many metal ions, surfactants, organic bases, *etc.*[1—4] The sulfophthaleins possess a range of specific features, such as the possibility of the separate existence of anionic protolytic forms, their stability, weak dimerization, good resolution of absorption bands of singly and doubly charged ions in the electronic spectra and, as a result, the high color contrast of indicator transitions.[1,4—7] In this class of compounds, bromo derivatives of sulfophthaneins (BDSP), such as bromophenol blue (BPB), bromocresol green (BCG), bromocresol purple (BCP), and bromothymol blue (BTB), have attracted attention. These BDSP are also used for the high precision *in situ* determination of pH of pure[8,9] and natural waters (a mixture of sulfophthaleins is used).[10,11] BDSP is the basis of sensitive elements of optical pH sensors,[12] fiber-optic biosensors, and chips[13—16] (*e.g.*, BTB and acetylcholine esterase doped with a sol-gel film are sensitive to the content of organophosphate pesticide).[14] Indicators are effectively used for the study of serum albumin.[17—20] One of the most promising fields of application of BDSP as analytical reagents is the quantitative determination of the range of components in bioagents and pharmaceuticals: antiviral (indinavir),[21] antimicrobial (enoxacin),[22] antibacterial (gatifloxacin,[23] sparfloxacin,[24] ofloxacin[25]), antihistaminic (oxomemazine),[26,27] and hypotensive (irbesartan,[28] nifedipine,[29] diltiazem[30]) agents, antidepressants (tianeptine,[31] trazodone,[32] sertraline, fluoxetine, venlafaxine[33]), antiulcer agents (ranitidine),[34] *etc.*[35,36] It is noteworthy that the high precision and rapid methods described above are based on the formation of heteroassociates (ionic pairs) between the component to be determined and the anionic forms of BDSP. Very often heteroassociates are extracted into an organic phase (tricloromethane,[21,22,25,27,29,30,32] dichloromethane[26,36]). Let us note that solutions of BDSP are rather complex, since each of the dyes is subjected to many protolytic and tautomeric transformations (even in a thin-film state BDSP can exist as an equilibrium mixture of associated lactone, quinoid, and zwitterionic forms[37—39]).

The literature data analysis suggests the importance of the study of cation-anion interactions (of both electrostatic and non-electrostatic interactions), resulting in the formation of heteroassociates consisting of anions (HAn^- and An^{2-}) of BDSP. It is obvious that not knowing the equilibrium and thermodynamic parameters of the association processes, it is impossible to effectively use BDSP. Previously,[40—43] the interactions of some sulfophthaleins with singly charged cationic polymethines (Ct^+) have been studied, and the equilibrium association constants (K_{as}) have been determined. However, the structure of associates and the energetic parameters of the association process remain unknown. In the present work, cation-anion interactions resulting in the formation of stoichiometric heteroassociates between singly and doubly charged BDSP anions and pinacyanol cations (PNC), quinaldine red (QR) were considered based on spectrophotometry results and quantum chemical calculations. The properties and the probable structure of heteroassociates with composition $Ct^+ + HAn^-$ and $Ct^+ + An^{2-}$ were discused. Besides, it was expedient to consider the properties of het-

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eroassociates of unsubstituted sulfophthalein, *viz.*, phenol red (PhR). It should be noted that PNC and QR cations proved to be appropriate counter ions for the study of properties of heteroassociates of many dyes due to their physicochemical properties.[44—47]

Experimental

Chlorides of pinacyanol and quinaldine red (Sigma) and disodium salts of sulfophthaleins (chemically pure) were used. The purity of each dye was controlled by spectrophotometry based on the known molar extinction coefficient (ε_{max}/L mol^{-1} cm^{-1}) in the absorption band maximum (λ_{max}) for the most intensely colored protolytic form. The medium acidity was maintained constant by phosphate, borate, and acetate buffer solutions and by the addition of HCl or NaOH. Additional experiments showed that the components of the buffer solutions used do not considerably influence the heteroassociation processes. The ionic strength (I) of the solutions used in photometric studies does not exceed 0.004 mol L^{-1}. The pH values were controlled with a glass electrode. The values of the optical density used in the calculations of the equilibrium association constants (K_{as}) were checked to correspond the Beer—Lambert—Bouguer law. The absorption spectra were recorded at ~20 °C using a Hitachi-U3210 or SF-46 spectrophotometers immediately after the preparation of the determined solutions. The error of λ_{max} values was ±0.5 nm. The general procedures of quantum-chemical calculations of dye structures and their ionic associates have been described earlier.[48]

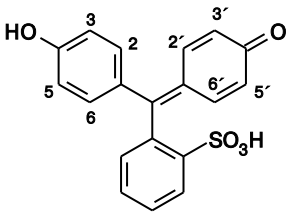
Results and Discussion

The state of dyes in aqueous solution. The equilibrium of BDSP and PhR as tribasic acids in solutions can be represented as follows: $H_3An^+ \rightleftarrows H_2An^0 \rightleftarrows HAn^- \rightleftarrows An^{2-}$. H_3An^+ cations are observed in dry acetonitrile.[49,50] The neutral forms of BDSP form the sultone tautomer, which is virtually colorless;[51] whereas samples recrystallized from concentrated acetic acid are body-colored. Anions, especially An^{2-}, are deeper colored, which favors the spectral study of the ionic association at very low (at the level $1 \cdot 10^{-6}$ mol L^{-1}) concentrations. The absorption bands of HAn^- and An^{2-} forms are well spectrally resolved, and the substantial differences between pK_{a_1} and pK_{a_2} values allow one to establish such a solution acidity, at which the only desired anionic protolytic form can exist. The values of λ_{max}, as well as the other spectral-protolytic characteristics of sulfophthaleins and polymethines, are listed in Tables 1 and 2.

The solutions containing singly charged cations (Ct^+) of polymethines in strongly acidic and basic media are considerably decolorized in consequence of the processes $Ct^+ + H^+ \rightleftarrows HCt^{2+}$ and $Ct^+ + OH^- \rightleftarrows CtOH$ correspondingly due to the disturbance of the conjugation of the polymethine chain of the chromophore.

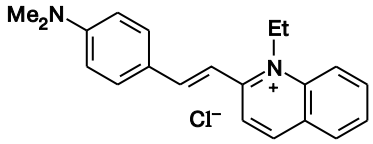
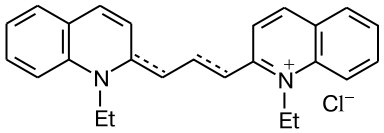
The interpretation of spectral changes in terms of the equilibrium approach (the use of the law of mass action for the determination of K_{as}) implies that the protolytic forms of interacting dyes will follow the main law of light absorption. In the studied concentration ranges of BDSP, PhR, and QR, the linear regression equations that follow this law are presented in Table 3. The dependence of the optical density on the content of the substance in solution is linear in relatively wide ranges of dye concentrations. As it follows from Table 3, the free terms of regression are statistically zero; therefore, we as-

Table 1. The spectral-protolytic characteristics* of sulfophthalein dyes

Structure	Name	Substituents	pK_{a_1}	pK_{a_2}	λ_{max}/nm (ε_{max}/L mol^{-1} cm^{-1})	
					HAn^-	An^{2-}
	3,3′,5,5′-Tetrabromophenolsulfophthalein (BPB)	3,3′,5,5′-Br	–0.95	4.20	438 ($2.5 \cdot 10^4$)	591 ($8.0 \cdot 10^4$)
	3,3′,5,5′-Tetrabromo-*m*-cresolsulfophthalein (BCG)	2,2′-Me; 3,3′,5,5′-Br	1.2	4.90	444 ($1.8 \cdot 10^4$)	617 ($4.0 \cdot 10^4$)
	5,5′-Dibromo-*o*-cresolsulfophthalein (BCP)	3,3′-Me; 5,5′-Br	–0.75	6.40	430 ($2.0 \cdot 10^4$)	588 ($4.3 \cdot 10^4$)
	3,3′-Dibromothymolsulfophthalein (BTB)	2,2-′Me; 3,3′-Br; 5,5′-Pr^i	–1.17	7.30	436 ($1.8 \cdot 10^4$)	616 ($4.13 \cdot 10^4$)
	Phenolsulfophthalein (PhR)	All — H	1.03	8.00	430 ($2.4 \cdot 10^4$)	558 ($6.2 \cdot 10^4$)

* Characteristics of sulfophtaleins were taken from the corresponding studies.[51—54] The errors in pK_a values are ±(0.03—0.08); λ_{max}, ±1 nm; ε_{max}, ±500 L mol^{-1} cm^{-1}.

Table 2. The spectral-protolytic characteristics* of polymethine dyes

Structure	Name	pK_{a_1}**	pK_{a_2}	λ_{max}/nm (ε_{max}/L mol^{-1} cm^{-1}), Ct^+
	2-[2-(4-Dimethylamino)phenyl]-ethenyl-1-ethylquinolinium (QR^+)	2.63	—	528 ($3.1 \cdot 10^4$)
	1-Ethyl-2-[3-(1-ethyl-1*H*-quinolin-2-ylidene)propenyl]quinolinium (PNC^+)	3.50	—	600, α-band ($1.2 \cdot 10^5$); 550, β-band; 510, γ-band

* Characteristics of QR and PNC were taken from the corresponding studies.[51,55—58] The errors in pK_a, λ_{max}, and ε_{max} are given in the note to Table 1.

** Values of pK_{a_1} for QR and PNC refer to the dissociation of the HCt^{2+} cation.

sumed that $A_i = kC$. It is noteworthy that the correlation coefficient is virtually equal to unity. This suggests that in the studied concentration ranges sulfophthaleins and QR almost do not undergo dimerization.

For PNC, as opposed to QR and sulfophthaleins, the main light absorption law is fulfilled at low concentrations ($3 \cdot 10^{-7}$—$1 \cdot 10^{-6}$ mol L^{-1}), because this polymethine undergoes substantial homoassociation (the properties of PNC in aqueous solution have been discussed earlier in more details).[58] The dimerization of PNC is spectroscopically manifested in a sharp weakening of α-band absorption and an increase in the β-band intensity (see Table 2).

In studies of interactions of HAn^- and An^{2-} with Ct^+ the medium acidity should be maintained so that it can provide the co-existence of only the corresponding ionic forms (in the opposite case the interpretation of spectral changes is complicated because of the possible interactions with the participation of other particles). To find the optimal association conditions, we calculated the fractions of the studied particles in aqueous solutions taking into account the protolytic processes listed above. As an example, the dependence of the content of dyes protolytic forms on the pH of aqueous solution ($I \to 0$; for BCG along with pK_1 and pK_2, the value of $pK_0 = -0.99$ is considered[59]) is shown in Fig. 1. Thus, from Fig. 1 it follows that for BCG it is reasonable to study the interaction of Ct^+ with HAn^- at pH ~3.5 (QR) and 4.2 (PNC) and of Ct^+ with An^{2-} at pH ≥ 7.

Association of Ct^+ with HAn^- and An^{2-}, the structures and the energetic parameters of associates. Analysis of changes in the electronic absorption spectra of the mixtures of Ct^+ with HAn^- and of Ct^+ with An^{2-} revealed the

Table 3. Equations of linear regressions of the main law of light absorbance

Ion	Equation*	Correlation coefficient
BPB^{2-}	$A_{591} = 0.00438_{(0.0080)} + 7.52 \cdot 10^4{}_{(2569)} \cdot C$, $C = 1.0 \cdot 10^{-6}$—$4.5 \cdot 10^{-5}$, $n = 8$	$0.99942_{(0.0036)}$
BCG^{2-}	$A_{617} = 0.000783_{(0.00387)} + 7.73 \cdot 10^3{}_{(45.3)} \cdot C$, $C = 1.5 \cdot 10^{-6}$—$2.5 \cdot 10^{-5}$, $n = 9$	$0.99988_{(0.010)}$
BCP^{2-}	$A_{588} = -0.0020_{(0.0023)} + 6.72 \cdot 10^4{}_{(130)} \cdot C$, $C = 5 \cdot 10^{-7}$—$4 \cdot 10^{-5}$, $n = 8$	$0.99999_{(0.0049)}$
BTB^{2-}	$A_{616} = -0.00066_{(0.0030)} + 3.92 \cdot 10^4{}_{(120)} \cdot C$, $C = 5 \cdot 10^{-7}$—$5 \cdot 10^{-5}$, $n = 8$	$0.99997_{(0.0061)}$
PhR^{2-}	$A_{558} = 0.00944_{(0.015)} + 6.76 \cdot 10^4{}_{(322)} \cdot C$, $C = 1 \cdot 10^{-6}$—$9 \cdot 10^{-5}$, $n = 9$	$0.9999_{(0.0054)}$
QR^+	$A_{528} = -0.0038_{(0.015)} + 3.37 \cdot 10^4{}_{(324)} \cdot C$, $C = 1 \cdot 10^{-6}$—$1 \cdot 10^{-4}$, $n = 9$	$0.9996_{(0.033)}$

* The lower index in the absorbance notation (A) corresponds to the wavelength (λ/nm), at which the dependence was determined, the lower indicies in parentheses show the standard deviation of the corresponding value; C/mol L^{-1} is the initial concentration of the dye ion; n is the amount of sampling of C values.

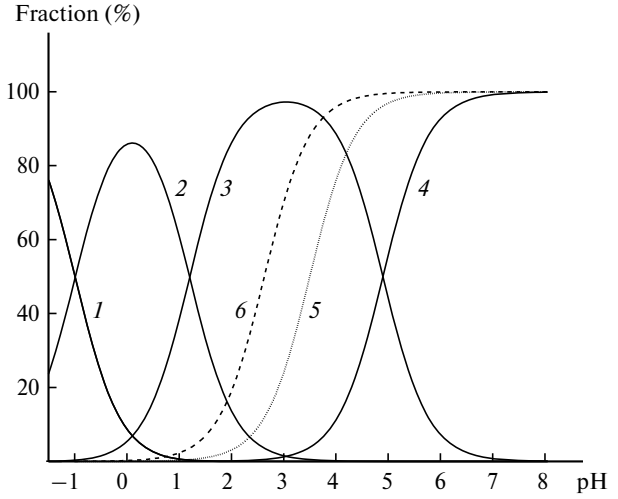


Fig. 1. The dependence of the content of protolytic forms of BCG H_3An^+ (*1*), H_2An (*2*), HAn^- (*3*), An^{2-} (*4*), and the PNC^+ (*5*) and QR^+ (*6*) cations in an aqueous solution on pH.

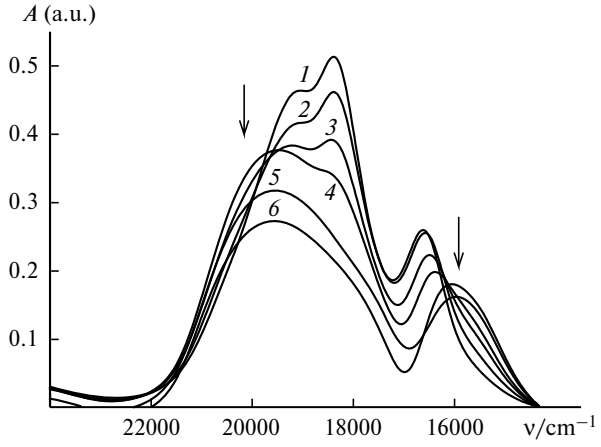


Fig. 3. The plot of the absorbance of a PNC solution (C = $= 4.9 \cdot 10^{-5}$ mol L^{-1}) *vs* the BCP concentration: $C_{BCP} = 0$ (*1*), $5.1 \cdot 10^{-6}$ (*2*), $1.5 \cdot 10^{-5}$ (*3*), $2.0 \cdot 10^{-5}$ (*4*), $3.0 \cdot 10^{-5}$ (*5*) and $5.0 \cdot 10^{-5}$ mol L^{-1} (*6*). The width of the absorbing layer is 0.20 cm, pH 9.2.

non-additivity of the spectral bands. Thus, the intensity of absorption of the mixture of the interacting counter ions is systematically lower than the total absorption of the individual dye ions. The characteristic criterion of association is the substantial decrease in the absorption intensity, which is clearly seen upon the addition of BDSP to the constant amount of polymethine (Figs 2 and 3). Let us note that this situation does not depend on the initial concentrations of anions or cations. For example, the initial concentrations of PNC in Figs 2 and 3 differ by approximately a factor of 100. In Fig. 2, for PNC the α-band intensity is higher than that of the β-band; in Fig. 3, *vice versa* (the systems $Ct^+ + HAn^-$ and $Ct^+ + An^{2-}$, respectively; the shift directions in the spectrum are shown by arrows).

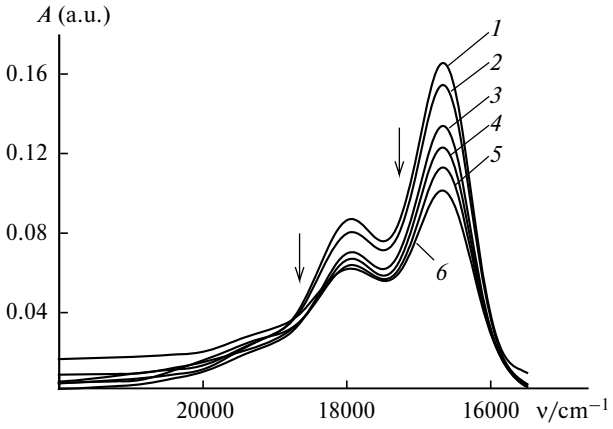


Fig. 2. The plot of the absorbance of a PNC solution (C = $= 4.9 \cdot 10^{-7}$ mol L^{-1}) *vs* the BCP concentration: $C_{BCP} = 0$ (*1*), $1.0 \cdot 10^{-6}$ (*2*), $3.5 \cdot 10^{-6}$ (*3*), $5.0 \cdot 10^{-6}$ (*4*), $9.9 \cdot 10^{-6}$ (*5*), and $1.5 \cdot 10^{-5}$ mol L^{-1} (*6*). The width of the absorbing layer is 5.00 cm, pH 4.3. Here and in Fig. 3 water (*1*) and a BCP solution in the corresponding concentration (*2*—*6*) were the reference solutions.

In the case of BDSP associates, the electrostatic attraction brings counter ions closer to each other. However, chromophore systems of polymethine cations and anions, as well as the energies of electronic transitions, are different. Besides, the distance between the counter ions in the heteroassociate is larger than that between the particles in usual dimers (the interplanar distance in the dimer of PNC Ct_2^{2+} does not exceed 3.9 Å,[58] whereas the distance between the counter ions in the $PNC^+ \cdot BTB^-$ associate is larger than 5 Å, see below). Therefore, the observed spectral changes upon the formation of associates with the participation of Ct^+ (a decrease in the absorption intensity without a substantial change in λ_{max}) are attributed to dispersion interactions, which are weakly sensitive to the differences in absorption regions of free counter ions.[44] The hypochromic effect of absorption bands of Ct^+ and the absence of new bands suggest the solvent-separated structure[44] of BDSP heteroassociates.

The estimation of the stoichiometric composition showed that at certain initial concentrations and molar ratios of counter ions, BDSP anions can form heteroassociates $Ct^+ \cdot HAn^-$ and $(Ct^+)_2 \cdot An^{2-}$ with Ct^+. The measure of the stability of these compounds is the equilibrium constant of association, which is determined from the law of mass action for the equilibria $Ct^+ + HAn^- \rightleftarrows$ $\rightleftarrows Ct^+ \cdot HAn^-$ and $2\,Ct^+ + An^{2-} \rightleftarrows (Ct^+)_2 \cdot An^{2-}$. Since in our experiments $I \leq 0.004$ mol L^{-1} and $I \to 0$, the concentration and thermodynamic values of K_{as} virtually coincide. The values of $K_{as} = [Ct^+ \cdot HAn^-] \cdot [Ct^+]^{-1} \cdot$ $\cdot [HAn^-]^{-1}$ and $K_{as} = [(Ct^+)_2 \cdot An^{2-}] \cdot [Ct^+]^{-2} \cdot [An^{2-}]^{-1}$ (in brackets there are the spectrophotometrically determined equilibrium molar concentrations of the corresponding particles) calculated from the spectroscopic data (by analogy with the literature data)[40,60,61] are listed in Table 4. In addition at higher concentrations of dye mix-

Table 4. The values of $\log K_{as}$ of BDSP associates

BDSP	$\log K_{as}$ (associate PNC^+/associate QR^+)*	
	$Ct^+ \cdot An^-$	$(Ct^+)_2 \cdot An^{2-}$
BTB	5.95±0.11/4.45±0.08	10.89±0.09/7.85±0.09
BCP	6.67±0.05/4.78±0.06	11.07±0.10/8.23±0.04
BCG	6.74±0.04/5.04±0.07	12.09±0.09/8.64±0.07
BPB	6.88±0.05/5.27±0.05	13.73±0.10/8.86±0.08

* The data on QR associates with doubly charged anions have been published previously.[62]

tures the turbidity and a change of the solution color are observed. This fact suggests the formation of associates of more complex stoichiometry and, probably, poorly soluble aggregates of different composition.

The values of K_{as} for singly and doubly charged anions cannot be compared directly. Nevertheless, from Table 4 it follows that PNC associates are considerably more stable than QR associates. The difference in stability is attributed, in particular, to an increase in the contribution of hydrophobic interaction in the pinacyanol associates. The hydrophobic contribution of quinolyl moiety in the PNC molecule is, apparently, more substantial than the contribution of *N*,*N*-dimethylaniline moiety in the QR molecule. In addition, the dispersion interactions manifested to a great extent in developed π-electron systems favor the association.[44,60] Due to specific structural features they are more inherent to the PNC^+ cation than to QR^+. Based on the K_{as} values, it can be noted that alkyl substituents are favorable for a decrease in K_{as}, whereas halogen atoms are favorable for its increase. It is due to the known fact[49—51] that alkyl groups lead to the nonplanarity of the molecule (and, as consequence, to an increase in the distance between the counter ions in the associate) and to a weakening of the contribution of dispersion interactions. On the contrary, bromine atoms virtually do not influence the BDSP geometry, but they substantially enhance the hydrophobic constituent of counter ion interactions. The increase in the number of bromine atoms, as well as a decrease in the number of alkyl substituents in the molecule, results in the increase in K_{as} for both the singly and doubly charged anions. For pinacyanol associates of BDSP the value of K_{as} increases in the series $BTB^- < BCP^- \approx BCG^- < BPB^-$ and $BTB^{2-} \approx BCP^{2-} < < BCG^{2-} < BPB^{2-}$, and for QR associates in the series $BTB^- < BCP^- < BCG^- < BPB^-$ and $BTB^{2-} < BCP^{2-} < < BCG^{2-} < BPB^{2-}$. It is natural that K_{as} has the largest value for the associates of the doubly charged anion of BPB, which contains the maximum number of bromine atoms and does not have alkyl substituents. It is notable that the stability of associates of PNC and QR of unsubstituted PhR is intermediate between that of BTB and BPB associates; $\log K_{as}$ is 5.83±0.10 for $PNC^+ \cdot PhR^-$ and 11.81±0.10 for $(PNC^+)_2 \cdot PhR^{2-}$(Ref. 62), whereas $\log K_{as}$ are 5.13±0.09 and 8.64±0.09 for $QR^+ \cdot PhR^-$ and $(QR^+)_2 \cdot PhR^{2-}$, respectively.

The formation of associates in solution is intrinsic for the dyes, whose molecules are planar, hydrophobic, and possess a π-conjugated electron system enhancing dispersion interactions. Among such dyes are squaraines,[63—66] spiropyrans,[67] some diazines, such as pyridazine, pyrazine,[68] porphyrins,[69] xanthenes,[70] mero- and thiacyanines,[71,72] have found application in the peptide study, the formation of J- and H-aggregates and Langmuir—Blodgett films.[65,67,71] In contrast to the above listed structures, BDSP anions (as well as other sulfophthaleins) cannot be assigned to planar π-electron systems. Nevertheless, as it follows from absorption spectra, a substantial interaction occurs between Ct^+ and BDSP anions. The data on the composition suggest that the planar polymethine cation coordinates nearby singly charged BDSP (or two cations are coordinated near the doubly charged anion). Therefore, it is reasonable to establish the most probable structure of stoichiometric heteroassociates by quantum chemical calculations and then compare their energetic parameters (in the first place, the enthalpies of formation, ΔH°_f).

It is known[73,74] that even for small molecules *ab initio* calculations result in the errors in ΔH°_f values larger than 100 kJ mol^{-1}. This is due to the incompleteness of the basis set used and to the fact that the electron correlation energy is not taken into account. An increase in the size of molecules leads to an increase in the error of ΔH°_f calculated by the *ab initio* method and these errors are to a great extent systematic in character. Hence, to estimate the values of ΔH°_f for ions and heteroassociates, we used the semiempirical AM1 method as one of extended variants of the MNDO method. The parameters of this method were selected so that they allow us to reproduce the experimental values of ΔH°_f of organic compounds in the best way. The average error in calculation of ΔH°_f is 25 kJ mol^{-1} (see Ref. 75). In addition, the values of ΔH°_f of dye ions were estimated by the semiempirical PM3 method (Table 5; MOPAC-2002, HyperChem 7.0 programs).[76]

The convergence gradient (RMS gradient is the rate of the energy change (first derivative) upon changes in the position of every atom in three mutually perpendicular directions; the local energy minimum is achieved when it becomes equal to zero) of consecutive iterations decreased from 4.2 to 0.04 kJ mol^{-1}. The scope of variation in ΔH°_f values (no more than 25.1 kJ mol^{-1}, BPB^- or BCP^-, PM3 method; 13.4 kJ mol^{-1}, PhR^{2-}, AM1 method) gives the good convergence of the results for both semiempirical methods (the maximum error is 5.4% (BPB^-), 4.1% (BCP^-) for the calculations by the AM1 method and 2.7% (PhR^{2-}) for PM3 calculations). The differences in the absolute values of ΔH°_f, obtained by two semiempirical methods are not principal in the terms of our aims. The maximum difference in the values calculated by the AM1

Table 5. The values of $\Delta H°_f$ of sulfophthalein ions, PNC, and QR calculated by AM1 and PM3 methods

Ion	$\Delta H°_f$/kJ mol^{-1}	
	AM1	PM3
BPB^-/BPB^{2-}	−465.8—−479.6/−473.1—−474.3	−435.8—−460.9/−450.0—−451.7
BCG^-/BCG^{2-}	−471.8—−481.4/−476.8—−478.5	−469.3—−478.1/−469.3—−472.6
BCP^-/BCP^{2-}	−583.7—−602.1/−554.8—−556.9	−584.5—−609.6/−566.5—−570.3
BTB^-/BTB^{2-}	−662.4—−681.7/−634.8—−639.8	−685.5—−691.4/−658.3—−666.6
PhR^-/PhR^{2-}	−556.0—−576.5/−479.3—−492.7	−575.7—−586.2/−534.2—−536.7
PNC^+	1076.8—1073.5	980.8—968.7
QR^+	989.3—984.2	918.8—912.6

and PM3 methods is 44 kJ mol^{-1} for PhR^{2-} (see Table 5); the largest negative values of $\Delta H°_f$ were selected as the final values.

Since the AM1 method is the method of choice for such calculations,[48,58] it was used to establish the structures of heteroassociates and their enthalpies of formation. To obtain the correct values of $\Delta H°_f$ of heteroassociates it is important to find the global energy minimum. For this aim we tested 6—7 different mutual positions of counter ions in heteroassociates (each counter ion was preliminary geometrically optimized with the AM1 method as described above). From the calculated set of energy (so-called local) minima the smallest minimum was selected; the energy of this structure was considered as the global energy minimum. Then we performed the additional geometry optimization of the structure of the heteroassociate, setting the range of diminishing values of the RMS gradient (as a rule, from 0.1 to $5 \cdot 10^{-3}$—$1 \cdot 10^{-4}$ kJ mol^{-1}). The completion of the optimization was determined by the absence of changes in $\Delta H°_f$ upon the change in the driven values of RMS (for the polymethine cations it often occurred at $5.0 \cdot 10^{-2}$—$5.0 \cdot 10^{-3}$ kJ mol^{-1}; for BDSP, at lower values). As an examples, the dependences of the value $\Delta H°_f$ on the RMS gradient for BTB heteroassociates are shown in Fig. 4; the course of the consecutive optimization of the geometric structure of the heteroassociate $PNC^+ \cdot BTB^-$ is shown in Table 6 (the stereo views are given for clarity; the position of the PNC^+ cation with respect to the anion is conventionally fixed; the hydrogen atoms are not shown). As it follows from Fig. 4 and Table 6, the geometry optimization is substantially dependent on the values of RMS, but it virtually finishes already at 0.01 kJ mol^{-1} and is accompanied by a decrease in the distance between counter ions.

The characteristics of dye ions and BTB heteroassociates are shown in Figs 5 and 6 as examples (AM1 method; the numbers nearby the arrows specify the scope of variations in $\Delta H°_f$/kJ mol^{-1} values of the corresponding particle). In Fig. 5 PNC^+ and BTB^- ions are characterized by $\Delta H°_f$ 1076.8—1073.5 and −662.4 to −681.7 kJ mol^{-1}, respectively. Their algebraic sum (414.4—391.8 kJ mol^{-1}, energy level *1*) is larger than $\Delta H°_f$ of the associate (255.2—240.5 kJ mol^{-1}, level *2*) by 173.9—136.6 kJ mol^{-1}. Similarly in Fig. 6 QR^+ and BTB^{2-} ions are characterized by $\Delta H°_f$ 989.3—984.2 kJ mol^{-1} and −634.8 to −639.8 kJ mol^{-1}, whereas two cations QR^+ have the energy of 1978.6—1968.4 kJ mol^{-1}. The algebraic sum of $\Delta H°_f$ of counter ions is 1343.8—1328.6 kJ mol^{-1} (level *1*). Since $\Delta H°_f$ of the heteroassociate was found to be equal to 740.0—703.5 kJ mol^{-1} (level *2*), the surplus of the algebraic sum of $\Delta H°_f$ of counter ions over $\Delta H°_f$ of the heteroassociate is 640.3—588.6 kJ mol^{-1}.

We calculated $\Delta H°_f$ values for all of the studied heteroassociates (Table 7). The algebraic sum (Σ) of the $\Delta H°_f$ values of corresponding ions in associates determined as $\Sigma = i\Delta H°_f(Ct) + \Delta H°_f(An)$, where i is the number of cations in the associate (second column), the differences $\Sigma - \Delta H°_f$ (fourth column), and the relative errors (%) of $\Sigma - \Delta H°_f$ calculation (fifth column), are given in Table 7. The Σ values were calculated using the data from Table 5.

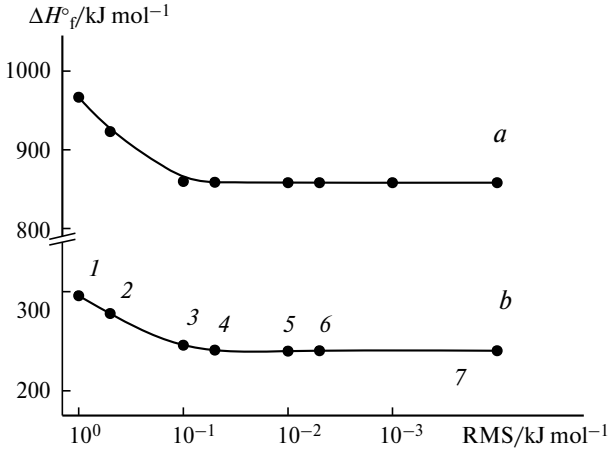
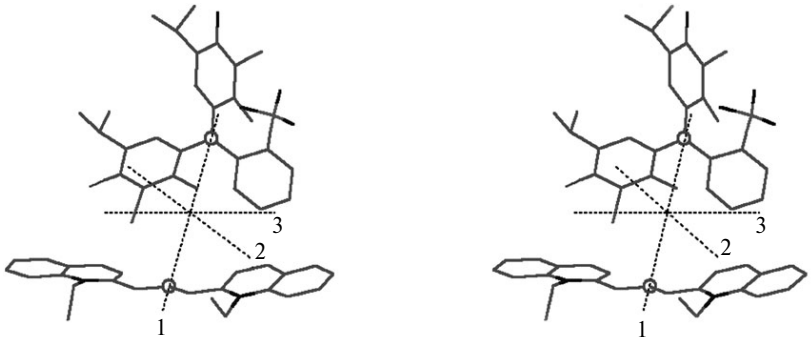
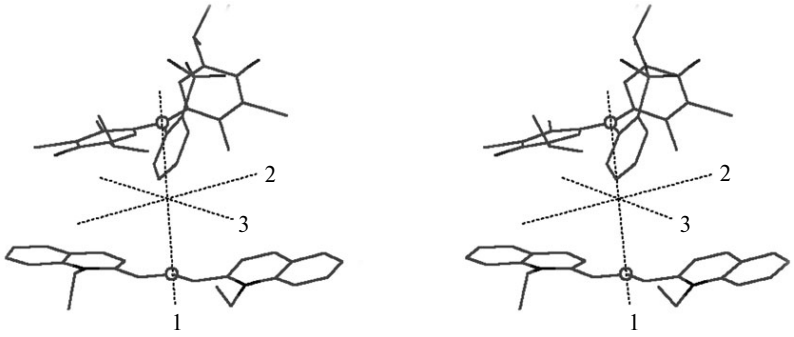
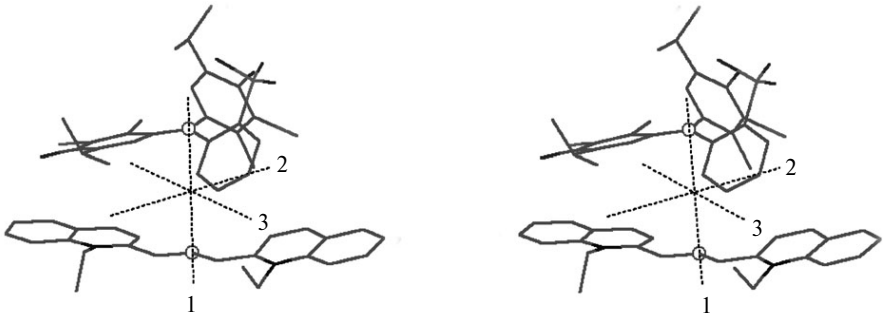
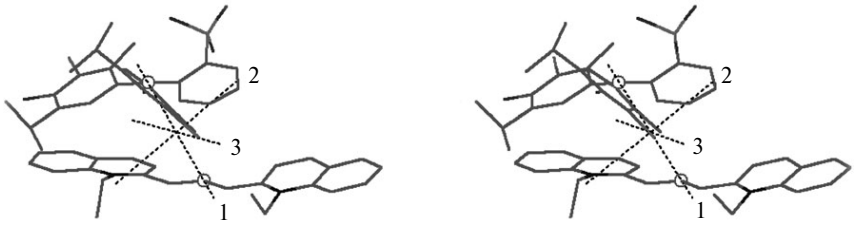
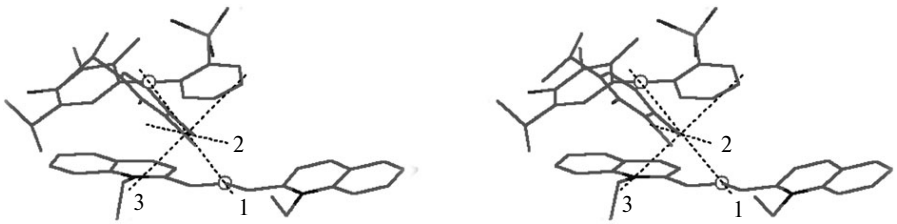


Fig. 4. The plot of $\Delta H°_f$ value *vs* the specified values of the RMS gradient: *a*, the associate of PNC^+ with BTB^{2-} anion; *b*, the associate of PNC^+ with the BTB^- anion (the points in the curve *b* correspond to the structures in Table 6: *1*, the initial position of geometry optimization; *2—6*, intermediate positions; *7*, the final position).

Table 6. Geometry optimization of the structure of the $PNC^+ \cdot BTB^-$ associate

RMS gradient*	Structure (stereo view, the anion is above the cation)	*d***/Å
1		6.9
2		6.7
3		6.1
4		5.8
5—7		5.5

* See Fig. 4.

** The distances between the labeled atoms.

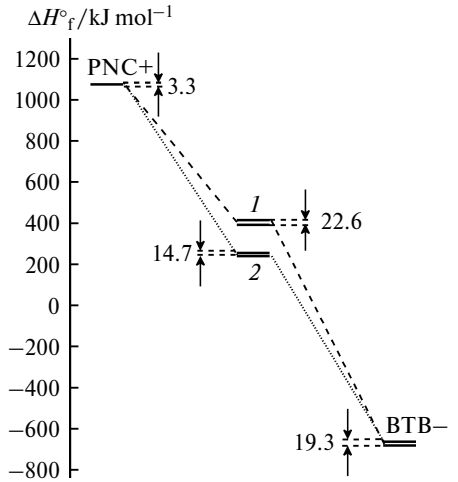


Fig. 5. The values of ΔH°_f of PNC^+ ions; BTB^-; the algebraic sum of ΔH°_f of ions composing the heteroassociate (*1*); ΔH°_f of the associate $PNC^+ \cdot BTB^-$ (*2*).

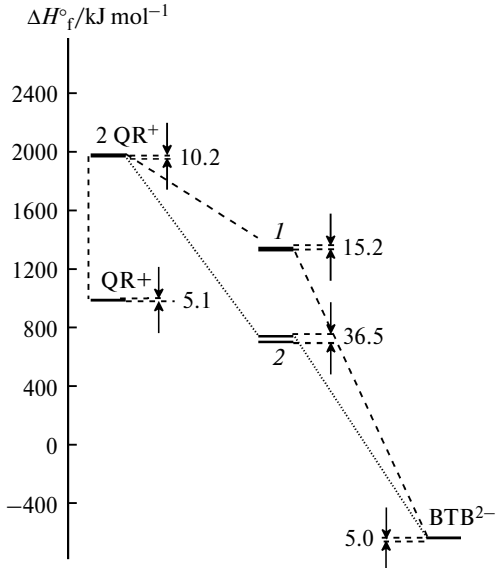


Fig. 6. The values of ΔH°_f of QR^+ ions; BTB^{2-}; the algebraic sum of ΔH°_f of ions composing the heteroassociate (*1*); ΔH°_f of the associate $(QR^+)_2 \cdot BTB^{2-}$ (*2*).

Based on the analysis of the data in Table 7 and the results obtained, a number of important conclusions can

Table 7. The energetic parameters of heteroassociates

Sulfophthalein	$\Sigma = i\Delta H^\circ_f(Ct) + \Delta H^\circ_f(An)$ /kJ mol^{-1} (I_{max}—I_{min})*	ΔH°_f of the heteroassociate/kJ mol^{-1} (II_{max}—II_{min})**	$(I_{max} - II_{min})$—$(I_{min} - II_{max})$ /kJ mol^{-1}	$\frac{(I_{max} - II_{min}) - (I_{min} - II_{max})}{I_{max} - II_{min}} \cdot 100$ (%)
		QR, $Ct^+ \cdot HAn^-$		
BPB	523.5—504.6	348.2—339.8	183.7—156.4	14.9
BCG	517.5—502.8	341.5—331.0	186.5—161.3	13.5
BCP	405.6—382.1	220.8—219.1	186.5—161.3	13.5
BTB	326.9—302.5	149.6—147.9	179.0—152.9	14.6
PhR	433.3—407.7	260.6—258.5	174.8—147.1	15.8
		QR, $(Ct^+)_2 \cdot An^{2-}$		
BPB	1505.5—1494.1	888.3—839.3	666.2—605.8	9.1
BCG	1501.8—1489.9	925.6—853.5	648.3—564.3	13.0
BCP	1423.8—1411.5	773.9—737.4	686.4—637.6	7.1
BTB	1343.8—1328.6	740.0—703.5	640.3—588.6	8.1
PhR	1499.3—1475.7	772.2—757.1	742.2—703.5	5.2
		PNC, $Ct^+ \cdot HAn^-$		
BPB	611.0—593.9	443.7—423.6	187.4—150.2	19.9
BCG	605.0—592.1	445.0—432.0	173.0—147.1	15.0
BCP	493.1—471.4	344.0—312.2	180.9—127.4	29.5
BTB	414.4—391.8	255.2—240.5	173.9—136.6	21.5
PhR	520.8—497.0	355.3—344.0	176.8—141.7	19.9
		PNC, $(Ct^+)_2 \cdot An^{2-}$		
BPB	1680.5—1672.7	1027.4—1011.0	669.5—645.3	3.6
BCG	1676.8—1668.5	1076.0—1060.5	616.3—592.5	3.9
BCP	1598.8—1590.1	951.1—928.1	670.7—639.0	4.7
BTB	1518.8—1507.2	887.9—858.1	660.7—619.3	6.3
PhR	1674.3—1654.3	1006.4—979.2	695.1—647.9	6.8

* I_{max} and I_{min} are the maximum and minimum values of Σ, respectively.
** II_{max} and II_{min} are the maximum and minimum values of ΔH°_f of the heteroassociate, respectively.

be drawn. Since the error in the calculated $\Sigma - \Delta H°_f$ value is not higher than the above mentioned average error of the method in the calculation of the values of $\Delta H°_f$, one can assert that the formation of BDSP heteroassociates is energetically favorable, especially in the case of heteroassociation of sulfophthaleins with the structures containing developed π-electronic systems (PNC); the gain in the energy is approximately 150—160 kJ mol^{-1} (heteroassociates of singly charged BDSP, see also Fig. 5) and 605—700 kJ mol^{-1} (heteroassociates of doubly charged BDSP, see Fig. 6).

The changes in $\Delta H°_f$ (vacuum) and K_{as} (aqueous solution) should not necessarily be in agreement. Besides, the semiempirical calculations cannot take into account some specific interactions (for example, hydrophobic interactions typical of bulky polyatomic counter ions of dyes). Nevertheless, the calculations revealed almost the same sequence of changes in $\Delta H°_f$ values, as for the experimental values of K_{as}; for singly charged BDSP the values of $\Delta H°_f$ increase in the series $BTB^- < BCP^- < BCG^- \leq BPB^-$; for doubly charged cations, in the series $BTB^{2-} < BCP^{2-} < BPB^{2-} \approx BCG^{2-}$. As in the case of K_{as}, the values of $\Delta H°_f$ of PhR heteroassociates have the intermediate values: BTB < PhR < BPB regardless of the composition. This fact supports the assumption that the presence of bromine atoms in the structure of sulfophthalein, in contrast to alkyl substituents, favors interactions with counter ions.

Hence, the values of K_{as} and $\Delta H°_f$ in the series of the structurally similar heteroassociates (such as BDSP associates) change in parallel. The systematic study of interactions of singly or doubly charged anions of sulfophthaleins with polymethine cations showed that heteroassociation of polyatomic particles is accompanied by a complex combination of Coulomb forces, hydrophobic, dispersion and, as a special case, π-electron interactions, the futher study of which implies the comparison of the results of spectroscopic measurements with the data of computer simulation.

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