

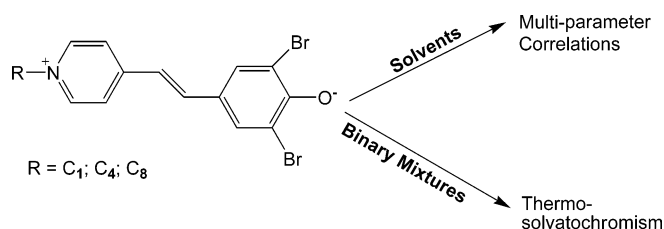
Thermosolvatochromism of Merocyanine Polarity Indicators in Pure and Aqueous Solvents: Relevance of Solvent Lipophilicity

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The following novel solvatochromic probes were synthesized: 2,6-dibromo-4-[(*E*)-2-(1-alkylpyridinium-4-yl)ethenyl] phenolate, where the alkyl groups are methyl, *n*-butyl, *n*-hexyl, and *n*-octyl, respectively. Solvatochromism of three of these probes (C₁, C₄, and C₈) was studied in 36 protic and aprotic solvents. A modified linear solvation energy relationship has been applied to the data obtained at 25 °C. Correlation of (empirical) polarities with other solvent properties showed more dependence on lipophilicity than on basicity. A similar conclusion has been reached for a series of other solvatochromic indicators. Exceptions are those that carry acidic hydrogens, being biased toward solvent basicity. Thermosolvatochromism has been studied in mixtures of water with methanol, 1-propanol, acetonitrile, and DMSO. Thermosolvatochromic data have been treated according to a model that explicitly considers the presence in bulk solution of three “species”: water, organic component, and solvent–water hydrogen-bonded aggregate. Solvation by the latter is favored over solvation by either of the two precursor solvents (aqueous DMSO is an exception). Temperature increase resulted in desolvation of the probes, due to concomitant decrease of the structures of the component solvents. The above-mentioned modified solvation equation has been successfully applied to solvatochromism in aqueous methanol and aqueous 1-propanol.

Introduction

We have been interested in studying the effects of solvents and binary solvent mixtures on the UV–vis spectra of solvatochromic probes or polarity indicators (hereafter referred to as “probes”),^{1–5} examples of which are shown in Figure 1, along with their p*K*_a and log *P*. The latter property is extensively

employed as a measure of lipophilicity or hydrophobic character; it refers to the partition coefficient of a substance between *n*-octanol and water: $\log P = \log([\text{substance}]_{n\text{-octanol}}/[\text{substance}]_{\text{water}})$.⁶ The probes shown in Figure 1 include 2,6-diphenyl-4-(2,4,6-triphenylpyridinium-1-yl) phenolate (RB); 2,6-dichloro-4-(2,4,6-triphenyl pyridinium-1-yl) phenolate (WB); 1-methylquinolinium-8-olate (QB); and 4-[(*E*)-2-(1-methylpyridinium-4-yl)ethenyl] phenolate (MePM) and 2,6-dibromo-4-[(*E*)-2-(1-butylquinolinium-4-yl)ethenyl] phenolate (BuQMBR₂), respectively. Note that log *P* is not available for RB because its solubility in water is negligibly small, ca. 7.2×10^{-6} mol/L.⁷

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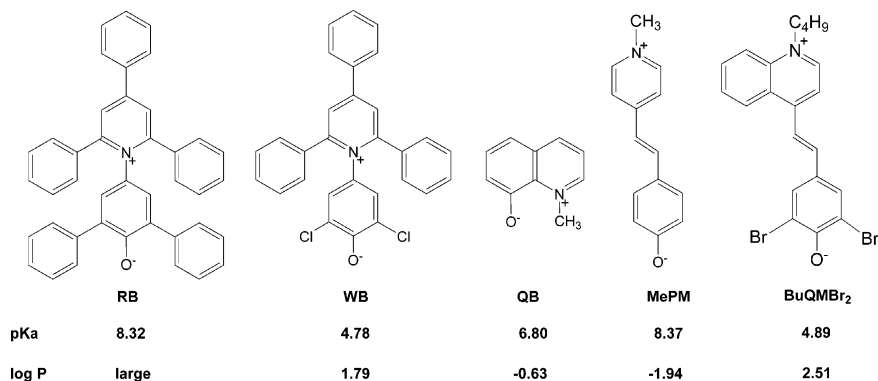


FIGURE 1. Structures, pK_a (conjugate acid), and log P of some solvatochromic probes.^{1–5,7}

An empirical solvent polarity scale, $E_T(\text{probe})$, is calculated from the UV–vis or fluorescence spectral data, as shown by eq 1:

$$E_T(\text{probe}) = 28591.5/\lambda_{\text{max}}(\text{nm}) \quad (1)$$

This equation converts the electronic transition within the probe into the corresponding intramolecular charge-transfer transition energy in kcal/mol.⁷ The solvent polarity scales of the probes depicted in Figure 1 are referred to as $E_T(30)$, $E_T(33)$, $E_T(\text{QB})$, $E_T(\text{MePM})$, and $E_T(\text{BuQMBr}_2)$, respectively. The dependence of $E_T(\text{probe})$ on solvent properties and, for binary solvent mixtures, on medium composition shed light on the relative importance of factors that contribute to solvation, in particular the pK_a and hydrophobic/hydrophilic character of both probe and solvent. We have also been interested in studying thermosolvatochromism (solvatochromism at different temperatures) because this bears on the effects of temperature on solvation and, in binary solvent mixtures, effects of temperature on the composition of the probe solvation coordination shell. An important application of this research is that the results obtained may be employed to understand effects of the medium on rate and equilibrium constants of chemical reactions. For example, the nonlinear dependences of the rate constants of the pH-independent hydrolysis of esters of different hydrophobicities (4-nitrophenyl chloroformate and 4-nitrophenyl heptafluorobutyrate, respectively) on medium composition (acetonitrile–water) are remarkably similar to the dependence of $E_T(\text{QB})$ and $E_T(33)$, respectively, on the same experimental variable. That is, the more hydrophilic probe, QB, serves as a model for the more hydrophilic ester (4-nitrophenyl chloroformate), whereas the more hydrophobic probe, WB, serves as a model for the perfluorobutyrate ester.⁸ This similar responses to solvent composition is very interesting because their origins are distinct, namely, a chemical reaction and an electronic transition, respectively.

The preceding paragraph shows that a clearer understanding of solvation requires the use of probes whose structures are modified in a systematic manner. The ones shown in Figure 1 differ widely in structure and hence in physicochemical properties that are relevant to their solvation. Consequently, quantification of the effects of a single property on solvation, e.g., pK_a or hydrophobicity, is not feasible because these properties change simultaneously for each pair of probes depicted. For example,

although RB is much more basic than WB, the response of both probes to solvent “acidity” or hydrogen-bond donation is similar. Briefly, whereas the ability of the solvent to form hydrogen bonds with the phenolate oxygen of RB is attenuated as a result of steric hindrance by the two ortho phenyl rings,⁹ the corresponding ability of WB is enhanced because of lower steric hindrance around the phenolate oxygen and the additional ability of two ortho chlorine atoms to form hydrogen bonds.¹

To address this problem, we have synthesized a series of novel merocyanine probes, RPMBr₂ where R = alkyl group, of identical pK_a and increasing hydrophobic character (see Figure 2); these were employed to measure the polarity of 36 protic and aprotic solvents. Values of $E_T(\text{RPMBr}_2)$ were found to correlate linearly with $E_T(30)$, which shows that the probes synthesized are sensitive to the same solute–solvent interactions as RB. Application of a modified multiparameter solvation equation has shown that $E_T(\text{RPMBr}_2)$ are sensitive to solvent dipolarity/polarizability, acidity, and lipophilicity but are little dependent on solvent basicity. We have also studied the thermosolvatochromism of RPMBr₂ in mixtures of water (W) with methanol (MeOH), 1-propanol (PrOH), acetonitrile (MeCN), and dimethylsulfoxide (DMSO). Values of $E_T(\text{RPMBr}_2)$ were found to increase as a function of increasing hydrophobicity of the probe; $E_T(\text{RPMBr}_2)/\text{CH}_2$ of the probe alkyl group was found to be similar to several Gibbs free energies of transfer of, e.g., alkylammonium halides from water to binary solvent mixtures. Temperature increase resulted in a gradual desolvation of the probes due to temperature-induced solvent structure perturbation. The modified multiparameter solvation equation was satisfactorily applied to MeOA–W and PrOH–W mixtures.

Results and Discussion

Probes Synthesized. A comment on the probes synthesized is in order. As expected, their pK_a's are identical, since Hammett σ_{para} of alkyl groups are similar, e.g., –0.17, –0.16, –0.15, for methyl, *n*-butyl, and *n*-pentyl, respectively;¹⁰ these groups are attached to the pyridinium ring where the small differences in their inductive effects are not transmitted to the phenolate oxygen. The solubility of OcPMBr₂ in water is very low; this introduces uncertainties in the determination of its E_T in water and of log P. The problem was solved as follows: E_T for this

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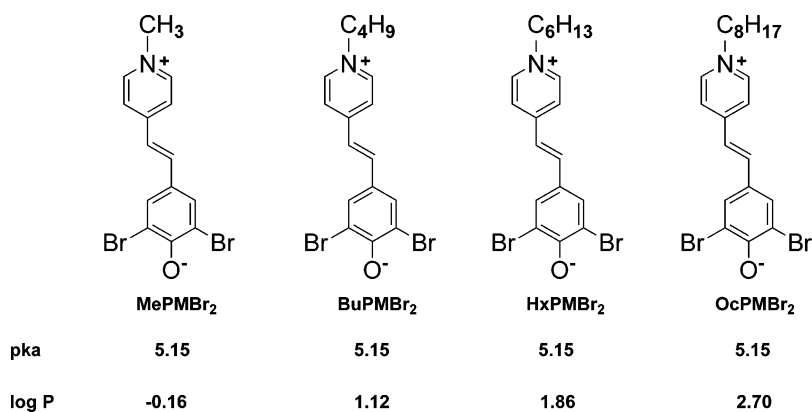


FIGURE 2. Structures, pK_a (conjugate acid), and log *P* of the merocyanine dyes synthesized. Groups longer than methyl are *n*-alkyl chains. See Experimental Section for determination of pK_a and log *P*.

probe was determined at different temperatures in binary mixtures of water ([W] = 40–52 mol/L or $\chi_w = 0.90$ –0.98, where χ refers to mole fraction) with the following solvents: MeOH, acetone (from 10 to 40 °C), PrOH, and MeCN (from 10 to 60 °C). Plots of $E_T(\text{OcPMBR}_2)$ in the different binary mixtures versus χ_w of water were found to be linear and converged to the value in pure water, as shown in Figure SI-1 (Figure 1 of Supporting Information). To check the validity of this approach, we repeated the experiment with HxPMBR₂, at 25 °C, in the same binary mixtures. Note that this probe is water-soluble; its E_T can be directly determined in water. Both $E_T(\text{HxPMBR}_2)$, i.e., that determined directly and by extrapolation, agreed within experimental uncertainty, 64.80 ± 0.15 kcal/mol.

The presence of a long chain alkyl group in the probe may, in principle, lead to its aggregation, especially in water or water-rich binary mixtures. In water, the UV–vis spectra of MePMBR₂, BuPMBR₂, and HxPMBR₂ showed no changes in λ_{max} and/or peak shape as a function of [probe] in the range 10⁻⁴–10⁻³ mol/L. This indicates that no probe aggregation occurs under our experimental conditions. For OcPMBR₂, Beer's law is obeyed in the concentration range from 4 × 10⁻⁶ to 5 × 10⁻⁵ mol/L, so that [OcPMBR₂] employed was 3 × 10⁻⁵ mol/L. The low solubility of OcPMBR₂ in water also precluded determination of a reliable log *P*. Therefore the corresponding value, 2.70 ± 0.1, was determined by extrapolation from the (linear) plot of log *P* versus number of carbon atoms in the probe alkyl chain, *N_c*, for MePMBR₂, BuPMBR₂, and HxPMBR₂, respectively (log *P* = -0.548 + 0.406 *N_c*; *r* = 0.9993, where *r* is the correlation coefficient). In summary, this novel series of probes is especially adequate to determine the relative importance of probe lipophilicity to its solvation.

Solvatochromism in Pure Solvents: A Modified Equation for Correlating $E_T(\text{probe})$ with Solvent Properties. Note: Details of all calculations performed are given in Calculations in Supporting Information.

Values of $E_T(\text{RPMBR}_2)$ for 34 organic solvents, including 18 protic, 4 chlorinated, and 12 polar aprotic are listed in Table 1. The corresponding values for H₂O and D₂O are listed in footnote *a* of the same table. $E_T(\text{RPMBR}_2)$ were found to correlate linearly with the $E_T(30)$ scale, as shown in Figure 3 and by eqs 2–4,

where SD is the standard deviation. This result is satisfying and can be explained by the fact that all probes are zwitterionic; the solvatochromic shift involves a $\pi \rightarrow \pi^*$ transition in the UV–vis region. That is, all merocyanine probes are sensitive to the same solute–solvent interactions as RB, e.g., Coulombic, dispersion, and hydrogen bonding. The magnitude of regression coefficients will be discussed below.

$$E_T(\text{MePMBR}_2) = 21.774 + 0.668E_T(30), r = 0.9685, \text{SD} = 1.1230 \quad (2)$$

$$E_T(\text{BuPMBR}_2) = 21.547 + 0.667E_T(30), r = 0.9727, \text{SD} = 1.0753 \quad (3)$$

$$E_T(\text{OcPMBR}_2) = 22.873 + 0.637E_T(30), r = 0.9691, \text{SD} = 1.0112 \quad (4)$$

Effects of solvent properties on $E_T(\text{probe})$ have been explained in terms of multiparameter equations, e.g., that of Taft–Kamlet–Abboud, eq 5, for a *single probe* in a series of solvents:^{12–14}

$$E_T(\text{probe}) = \text{constant} + s(\pi_{\text{solv}}^* + d\delta) + a\alpha_{\text{solv}} + b\beta_{\text{solv}} + h(\delta_{\text{H}}^2) \quad (5)$$

Here $E_T(\text{probe})$ is modeled as a linear combination of a dipolarity/polarizability term [$s(\pi_{\text{solv}}^* + d\delta)$], two hydrogen-bonding terms, in which the solvent is the hydrogen-bond donor ($a\alpha_{\text{solv}}$) and/or the hydrogen-bond acceptor ($b\beta_{\text{solv}}$), and a cavity term ($h(\delta_{\text{H}}^2)$). The later is redundant when the “Frank-Condon principle” is obeyed, as in case of the probes studied. The parameters π_{solv}^* , α_{solv} , and β_{solv} are known as solvatochromic parameters; we use the subscript (solv) so that they are not confused with the same symbols, e.g., α and β of the Brønsted catalysis equation. In applying eq 5, care should be exercised in order to obtain meaningful statistical correlations. For example, the solvatochromic parameters tested should not correlate linearly, and a sufficient number of solvents, usually

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TABLE 1. Solvent Polarity, $E_T(\text{probe})$ (kcal mol⁻¹, at 25 °C), Based on the Solvatochromic Probes MePMBBr₂, BuPMBBr₂, and OcPMBBr₂, Respectively^a

	solvent	$E_T(\text{MePMBBr}_2)$	$E_T(\text{BuPMBBr}_2)$	$E_T(\text{OcPMBBr}_2)$
Normal-Chain Alcohols				
1	methanol	59.24	58.65	58.54
2	ethanol	56.03	55.60	55.56
3	1-propanol	54.88	54.40	54.40
4	1-butanol	54.15	53.75	53.74
5	1-hexanol	53.07	52.81	52.81
6	1-octanol	52.26	52.08	51.99
Branched-Chain Alcohols, Other Alcohols, 2-Alkoxyethanols				
7	2-propanol	53.54	53.07	53.02
8	2-butanol	52.29	52.01	51.90
9	2-methyl-2-propanol	50.59	50.40	50.30
10	3-methyl-1-butanol	53.32	52.97	52.97
11	1,2-ethanediol	61.27	60.79	60.70
12	benzyl alcohol	54.56	54.28	54.25
13	cyclohexanol	52.50	52.16	52.12
14	2-methoxyethanol	56.97	56.43	56.28
15	2-ethoxyethanol	55.52	54.99	54.96
16	2-propoxyethanol	54.60	54.18	54.22
17	2-butoxyethanol	54.10	53.72	53.69
18	2-(2-methoxy-ethoxy)ethanol	55.42	54.76	54.76
Chlorinated and Aromatic Solvents				
19	chloroform	46.12	46.246	46.25
20	dichloromethane	48.13	48.134	48.15
21	1,2-dichloroethane	48.55	48.522	48.52
22	chlorobenzene		45.71	45.70
Polar Aprotic Solvents				
23	acetone	51.06	50.83	50.82
24	acetonitrile	53.32	52.89	52.99
25	<i>N,N</i> -dimethylacetamide	51.98	51.59	51.52
26	<i>N,N</i> -dimethylformamide	52.39	52.00	52.02
27	1,3-dimethyl-2-imidazolidinone	51.83	51.23	51.23
28	DMSO	53.41	52.68	53.02
29	1,4-dioxane	45.69	45.65	45.65
30	ethyl acetate		47.61	47.55
31	ethylene glycol dimethylether	48.72	48.32	48.30
32	nitromethane	53.14	52.85	52.83
33	pyridine	49.66	49.40	49.40
34	THF	47.69	47.40	47.44

^a $E_T(\text{probe})$ values of water were found to be 65.24, 64.98, and 64.65 kcal/mol for MePMBBr₂, BuPMBBr₂ and OcPMBBr₂, respectively. The last value was determined by extrapolation; see text for details. $E_T(\text{probe})$ values of D₂O were found to be 65.57 and 65.06 kcal/mol for MePMBBr₂, BuPMBBr₂, respectively

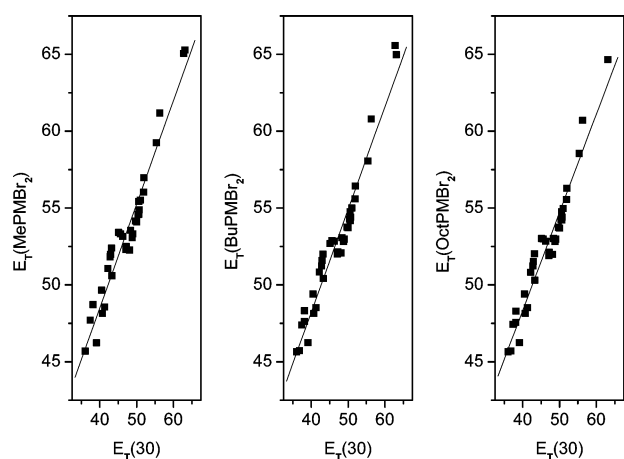


FIGURE 3. Plots of $E_T(\text{RPMBBr}_2)$ versus $E_T(30)$ for the solvents investigated. Values of the former E_T are from Table 1; the latter are those published elsewhere.^{7,11}

5 per each solvent property is employed;^{1–5,12,13} these conditions are met in the present work.

Although we have shown that zwitterionic probes are sensitive to solvent lipophilicity,^{1–5} the relative importance of this

property could not be assessed because of the small number of probes and solvents tested. Therefore, we examined a possible modification of eq 5, based on both chemistry and statistics, namely, by adding a term for solvent hydrophobicity, as shown by eq 6:

$$E_T(\text{probe}) = \text{constant} + s(\pi_{\text{sol}}^* + d\delta) + a\alpha_{\text{sol}} + b\beta_{\text{sol}} + p \log P_{\text{sol}} \quad (6)$$

where $\log P_{\text{sol}}$ refers to the partition coefficient of the solvent between *n*-octanol and water. This lipophilicity term has been included by analogy to similar linear solvation energy relationships for solutes. For example, solubilities, distribution between immiscible solvents, and other properties that depend on solute–solvent interactions have been modeled by equations that correlate the property of interest with solvatochromic parameters and molar volume of the solute.^{15,16} $\log P_{\text{sol}}$ in *n*-octanol/W has been employed because more data are available for this biphasic system; in principle other lipophilicity scales may be

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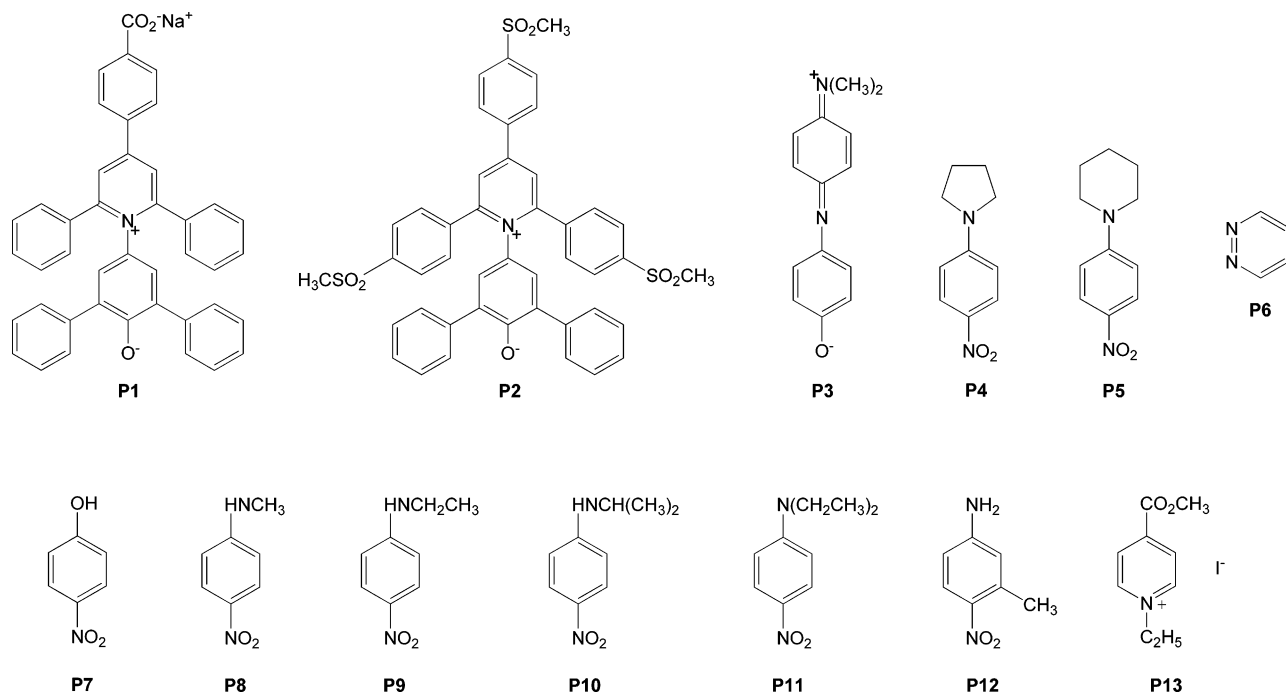


FIGURE 4. Structures of additional probes employed in the multicorrelation analysis equation (eq 6). P1, sodium-{4-[4-(4-carboxylatophenyl)-2,6-diphenyl-1-pyridinio]-2,6-diphenolate}; P2, 4-[2,4,6-tris[(4-methanesulfonyl)phenyl]-1-pyridinio]-2,6-diphenylphenolate; P3, phenol blue; P4, *N*-(4-nitrophenyl) pyrrolidine; P5, *N*-(4-nitrophenyl) piperidine; P6, pyridazine; P7, 4-nitrophenol; P8, *N*-methyl-4-nitroaniline; P9, *N*-ethyl-4-nitroaniline; P10, *N*-isopropyl-4-nitroaniline; P11, *N,N*-diethyl-4-nitroaniline; P12, 3-methyl-4-nitroaniline; P13, *N*-ethyl-4-carbomethoxy pyridinium iodide.¹⁸

employed, e.g., those based on partition between water and dichloroethane; chloroform or heptane. Note that these lipophilicity scales are linearly correlated with the *n*-octanol/W system.¹⁷

Because the cavity term was dropped, eq 5 contains three solvent parameters, whereas eq 6 contains four. Therefore, it is necessary to determine whether including an additional term is statistically significant; alternatively, whether β_{solv} may be dropped from eq 6, leading to a three-term equation. This statistical test relies on (1) use of a sufficiently large solvatochromic data set; (2) use of a stepwise correlation procedure, i.e., E_T (probe) is correlated with two, three, and four solvent parameters followed, in each case, by examination of the goodness of fit. With regard to point 1, we used the solvatochromic data of 21 probes, namely, the five probes shown in Figures 1, three of the probes of Figure 2 ($R = \text{Me, Bu, and Oc}$) and the 13 probes, P1, P2, etc., of Figure 4.¹⁸ The probes selected represent different chemical classes, this is expected to lead to differences in the contributions of solvation mechanisms (hydrogen bonding; solute dipole-solvent dipole interactions, etc.); the number of solvents tested is large enough to secure statistically valid correlations, *vide supra*. Point 1 will be examined first, based on four solvent parameters.

The regression coefficients of eq 6 are listed in Table SI-1 (Table 1 in Supporting Information). They permit a comparison of the response of different probes to the *same* solvent property, e.g., acidity or basicity. They do not permit, however, a direct comparison of the relative importance of solvent properties to the solvation of *different* probes. The reason is that E_T (probe)

and the solvent properties tested (α_{solv} , β_{solv} , etc.) have different scales. Use of the *standardized* coefficients, $\beta_{\text{statistical}}$, however, solves this problem (see Calculations in Supporting Information);¹⁹ these are listed in Table 2.

Several points merit comments:

1. We address the relative magnitudes of $\beta_{\text{statistical}}$ of basicity b and lipophilicity p . Although data scatter for the former property is high, $\beta_{\text{statistical}}$ of $p > \beta_{\text{statistical}}$ of b for the probes synthesized and for MePM, BuQMBr₂, RB, WB, P1, P6, P11, and P13. This indicates that these probes are more sensitive to solvent lipophilicity than to its basicity, as argued above. The only probes for which $\beta_{\text{statistical}}$ of $b > \beta_{\text{statistical}}$ of p are those that carry a relatively acidic hydrogen, namely, P7, P8, P9, P10, and P12, being understandably more sensitive to solvent basicity. In fact, these probes have been employed to determine β_{solv} because their solvatochromic behavior is dominated by their response to solvent basicity.²⁰

2. With regard to point 2 above, the minimum number of variables that satisfactorily describes the phenomenon investigated (dependence of E_T (probe) on solvent properties) should be sought.²¹ Therefore, we examined the dependence of the multiple-linear regression coefficient (r^2) and $\beta_{\text{statistical}}$ on the number of solvent properties employed. It is not practical to list and discuss the results of this stepwise variation for the 21 probes examined, due to the excessive number of regression equations (84) resulting from, *per probe*, one equation with two variables, two equations with three variables, and one equation with four variables. Therefore, we discuss the results of three

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TABLE 2. $\beta_{\text{statistical}}$ Coefficients of Equation 6 for the Probes Synthesized and Those of Figures 1, 2, and 4

probe	$\beta_{\text{statistical}}(s)$	$\beta_{\text{statistical}}(a)$	$\beta_{\text{statistical}}(b)$	$\beta_{\text{statistical}}(p)$	r^2	n^a
MePMBR ₂	0.46 (± 0.07)	0.81 (± 0.06)	0.02 (± 0.07)	-0.24 (± 0.07)	0.9258	36
BuPMBR ₂	0.44 (± 0.07)	0.80 (± 0.06)	-0.01 (± 0.07)	-0.21 (± 0.07)	0.9334	35
OcPMBR ₂	0.43 (± 0.07)	0.79 (± 0.06)	-0.01 (± 0.07)	-0.22 (± 0.07)	0.9317	35
MePM	0.43 (± 0.09)	0.92 (± 0.08)	-0.06 (± 0.08)	-0.15 (± 0.07)	0.9542	36
BuQMBR ₂	0.28 (± 0.06)	0.82 (± 0.07)	-0.23 (± 0.09)	-0.35 (± 0.08)	0.9011	36
RB	0.47 (± 0.09)	0.80 (± 0.06)	0.03 (± 0.06)	-0.06 (± 0.09)	0.8677	57
WB	0.37 (± 0.07)	0.80 (± 0.06)	-0.02 (± 0.09)	-0.08 (± 0.08)	0.9412	25
QB	0.29 (± 0.07)	0.85 (± 0.06)	0.01 (± 0.07)	-0.02 (± 0.10)	0.9415	24
P1	0.28 (± 0.06)	0.88 (± 0.05)	-0.08 (± 0.05)	-0.14 (± 0.06)	0.9704	19
P2	0.41 (± 0.07)	0.89 (± 0.07)	0.08 (± 0.08)	0.08 (± 0.09)	0.9500	20
P3	-0.84 (± 0.18)	-0.13 (± 0.06)	0.09 (± 0.09)	0.02 (± 0.19)	0.9459	23
P4	-0.70 (± 0.12)	-0.34 (± 0.09)	0.23 (± 0.10)	0.12 (± 0.15)	0.8867	24
P5	-0.67 (± 0.12)	-0.32 (± 0.09)	0.13 (± 0.11)	0.12 (± 0.15)	0.8880	23
P6	0.34 (± 0.06)	0.86 (± 0.03)	-0.09 (± 0.05)	-0.11 (± 0.07)	0.9902	20
P7	-0.52 (± 0.09)	-0.07 (± 0.06)	-0.73 (± 0.07)	0 (± 0.12)	0.9491	23
P8	-0.72 (± 0.06)	-0.22 (± 0.05)	-0.54 (± 0.07)	0.03 (± 0.09)	0.9672	21
P9	-0.74 (± 0.12)	0.14 (± 0.11)	-0.48 (± 0.13)	0.02 (± 0.18)	0.8748	21
P10	-0.68 (± 0.05)	-0.23 (± 0.04)	-0.45 (± 0.05)	0.14 (± 0.08)	0.9777	21
P11	-0.86 (± 0.06)	-0.29 (± 0.05)	0.08 (± 0.07)	0.16 (± 0.09)	0.9664	21
P12	-0.50 (± 0.04)	-0.15 (± 0.04)	0.86 (± 0.04)	0.04 (± 0.05)	0.9833	20
P13	0.30 (± 0.08)	0.85 (± 0.05)	-0.02 (± 0.06)	-0.15 (± 0.11)	0.9746	20

^a Number of solvents tested.

TABLE 3. Results Obtained by Stepwise Multilinear Regression Analysis of the Dependence of $E_T(\text{probe})$ on Solvent Properties^a

	$E_T(\text{BuPMBR}_2)$	r^2	$E_T(30)$	r^2	$E_T(P7)$	r^2	
	$E_T(\text{probe}) = a \alpha_{\text{solv}} + s (\pi_{\text{solv}}^* + d \delta)$		$E_T(P7) = b \beta_{\text{solv}} + s (\pi_{\text{solv}}^* + d \delta)$				
$\beta_{\text{statistical}}(a)$	0.78 (± 0.06)	0.9140	0.81 (± 0.05)	0.8668	$\beta_{\text{statistical}}(b)$	-0.74 (± 0.07)	0.9448
$\beta_{\text{statistical}}(s)$	0.52 (± 0.07)		0.43 (± 0.05)		$\beta_{\text{statistical}}(s)$	-0.49 (± 0.06)	
	$E_T(\text{probe}) = a \alpha_{\text{solv}} + s (\pi_{\text{solv}}^* + d \delta) + p \log P_{\text{solv}}$		$E_T(P7) = b \beta_{\text{solv}} + s (\pi_{\text{solv}}^* + d \delta) + p \log P_{\text{solv}}$				
$\beta_{\text{statistical}}(a)$	0.79 (± 0.05)	0.9337	0.81 (± 0.05)	0.8673	$\beta_{\text{statistical}}(b)$	-0.74 (± 0.07)	0.9448
$\beta_{\text{statistical}}(s)$	0.44 (± 0.06)		0.47 (± 0.09)		$\beta_{\text{statistical}}(s)$	-0.49 (± 0.09)	
$\beta_{\text{statistical}}(p)$	-0.21 (± 0.07)		0.06 (± 0.09)		$\beta_{\text{statistical}}(p)$	0 (± 0.11)	
	$E_T(\text{probe}) = a \alpha_{\text{solv}} + s (\pi_{\text{solv}}^* + d \delta) + b \beta_{\text{solv}}$		$E_T(P7) = b \beta_{\text{solv}} + s (\pi_{\text{solv}}^* + d \delta) + a \alpha_{\text{solv}}$				
$\beta_{\text{statistical}}(a)$	0.77 (± 0.07)	0.9139	0.80 (± 0.06)	0.8671	$\beta_{\text{statistical}}(b)$	-0.72 (0.07)	0.9485
$\beta_{\text{statistical}}(s)$	0.56 (± 0.06)		0.02 (± 0.06)		$\beta_{\text{statistical}}(s)$	-0.49 (0.06)	
$\beta_{\text{statistical}}(b)$	0.02 (± 0.07)		0.42 (± 0.05)		$\beta_{\text{statistical}}(a)$	-0.07 (0.06)	
	$E_T(\text{probe}) = a \alpha_{\text{solv}} + s (\pi_{\text{solv}}^* + d \delta) + p \log P_{\text{solv}} + b \beta_{\text{solv}}$		$E_T(P7) = b \beta_{\text{solv}} + s (\pi_{\text{solv}}^* + d \delta) + p \log P_{\text{solv}} + a \alpha_{\text{solv}}$				
$\beta_{\text{statistical}}(a)$	0.80 (± 0.06)	0.9338	0.47 (± 0.09)	0.8677	$\beta_{\text{statistical}}(b)$	-0.73 (± 0.07)	0.9491
$\beta_{\text{statistical}}(s)$	0.44 (± 0.07)		0.80 (± 0.06)		$\beta_{\text{statistical}}(s)$	-0.52 (± 0.10)	
$\beta_{\text{statistical}}(p)$	-0.21 (± 0.07)		0.03 (± 0.06)		$\beta_{\text{statistical}}(p)$	-0.01 (± 0.08)	
$\beta_{\text{statistical}}(b)$	-0.13 (± 0.07)		-0.06 (± 0.09)		$\beta_{\text{statistical}}(a)$	-0.08 (± 0.06)	

b- $E_T(\text{probe})$ data at 25 °C, taken from the references listed in Table 2.

representative probes, namely, BuPMBR₂ (model for merocyanines), RB (model for WB and QB), and P7 (probe biased toward solvent basicity, model for P8 and P12); see Table 3.

Table 3 shows that $E_T(\text{BuPMBR}_2)$ is reasonably correlated by two solvent properties, namely, α_{solv} and $s \pi_{\text{solv}}^*$. Inclusion of $\log P$ resulted in a better fit to the data (increase of r^2) relative to inclusion of β_{solv} ; use of four solvent properties produced no further improvement. On the other hand, $E_T(30)$ and $E_T(P7)$ may be conveniently described by two solvent properties, α_{solv} , π_{solv}^* and β_{solv} , π_{solv}^* , respectively.

It is possible that the lower significance of β_{solv} is due to inefficient interactions between the solvent (as electron donor) and the heterocyclic quaternary nitrogen of the zwitterionic probe. For example, whereas the $(\text{CH}_3)_4\text{N}^+$ ion has no effect on the structure of water, $(n\text{-C}_4\text{H}_9)_4\text{N}^+$ has a net structure-enhancing effect due to hydrophobic hydration of the alkyl groups.²² On the other hand, addition of β_{solv} to the equation that describes the dependence of Gibbs free energies of solution

of tetra-alkylammonium halides on solvent properties did not increase the overall correlation coefficient, so β_{solv} was dropped.²³ As expected, only solvent basicity and dipolarity/polarizability are relevant to solvation of P7.

3. The slopes of eq 2–4 are ca. 0.65, indicating that the overall solvatochromic responses of the probes synthesized are lower than that of RB. What is relevant, however, is the probe response to individual properties of the solvent, as given by the left-hand terms of eq 6. Interestingly, $\beta_{\text{statistical}}$ of s , a , and b for the probes synthesized are not different from those of RB; they are more sensitive to solvent hydrophobicity. On the basis of these results, they may substitute RB where this is advantageous, e.g., in relatively acidic buffered solutions, where protonation of its phenolate oxygen leads to loss of solvatochromic response;

4. Introduction of two bromine atoms in the structure of the precursor merocyanine, MePM, has resulted in the response expected, i.e., a decrease in $\beta_{\text{statistical}}$ of a , due to lower pK_a ,

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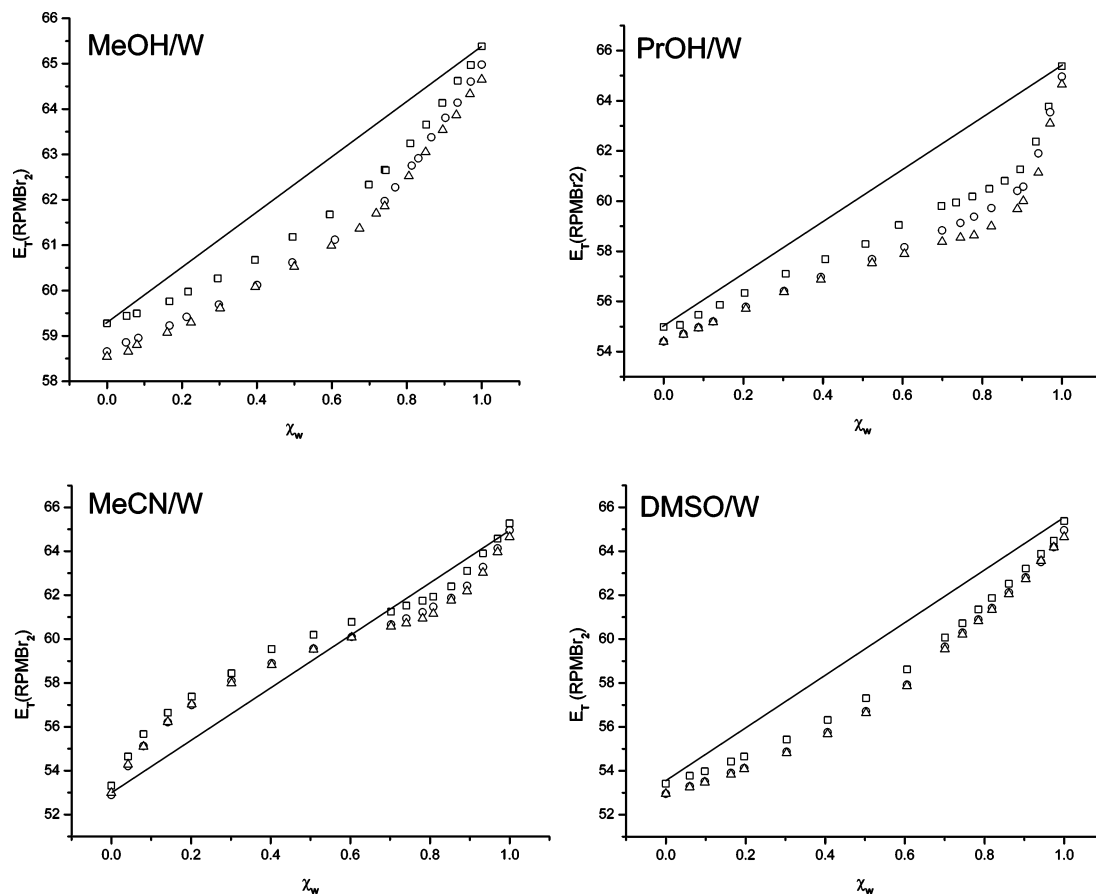


FIGURE 5. Dependence of the empirical solvent polarity parameter $E_T(\text{RPMBR}_2)$ on the mole fraction of water, χ_w , at 25 °C, for mixtures of water with methanol, MeOH, 1-propanol, PrOH, acetonitrile, MeCN, and dimethylsulfoxide (DMSO), respectively. The straight lines were plotted to guide the eye and represent ideal solvation of the dye by the mixture; see text for details. Probe symbols: (□) MePMBR₂; (○) BuPMBR₂; and (Δ) OcPMBR₂.

and an increase in $\beta_{\text{statistical}}$ of p , because bromine is more lipophilic than hydrogen.²⁴

In summary, the Taft-Kamlet-Abboud equation may be expanded to include solvent lipophilicity, as given by $\log P$ (or any equivalent scale). At least for merocyanines, the basicity term may be dropped from eq 6, so that solvent polarity is described in terms of its acidity, dipolarity/polarizability and lipophilicity. Equation 6 is general, unless the structure of the probe makes it particularly sensitive (or biased) toward a single property of the solvent.

Thermosolvatochromism in Binary Solvent Mixtures. Nonlinear Dependence of $E_T(\text{RPMBR}_2)$ on χ_w . Figure 5 shows the dependence of $E_T(\text{RPMBR}_2)$ on solvent composition at 25 °C, for the three probes synthesized, in four binary mixtures. All plots shown in Figure 5 are nonlinear; this may be attributed to several factors and/or solute–solvent interaction mechanisms. Nonideal behavior may originate from dielectric enrichment, i.e., enrichment of the solvation coordination shell in the solvent of higher relative permittivity, ϵ .²⁵ This mechanism may be rejected, however, because if dielectric enrichment were operative, all curves of Figure 5 should lie above, not below, the straight line that connects the polarities of the two pure liquids. A part of the data of MeCN lies above the line, but there is no reason to believe that dielectric enrichment is operative only

for this solvent and not for others of still higher ϵ (= 78.36, 32.66, 20.45, 46.45, and 35.94 for W, MeOH, PrOH, DMSO, and MeCN, respectively).

Another reason for nonideal behavior is preferential solvation of the probe by a component of the mixture due to solute–solvent specific interactions, e.g., hydrogen bonding and dipole–dipole interactions. A large body of experimental data and theoretical calculations, e.g., of the Buff-Kirkwood integral functions (that describe W–W, Solv–Solv, and Solv–W interactions), has shown that the binary mixtures employed are microheterogeneous; there exist microdomains composed of organic solvent surrounded by water and of water solvated by organic solvent. The onset and composition of these microdomains depend on the pair of solvents. There exists the possibility of preferential solvation of the probe in the less polar microdomains, leading to below-the-line deviation, as shown in Figure 5.^{25–28} In summary, nonideal solvation behavior is not unexpected.

Response of $E_T(\text{probe})$ to Lipophilic Character of the Probe. Figure 5 clearly shows that the deviation from linearity increases as a function of increasing N_c of the probe, i.e., its hydrophobic character. Plots (not shown) of $E_T(\text{solvent})$ versus N_c gave slopes of ca. 0.1 kcal/CH₂ in water and 0.33 ± 0.18 kcal/CH₂ at the points of maximum deviation from linearity

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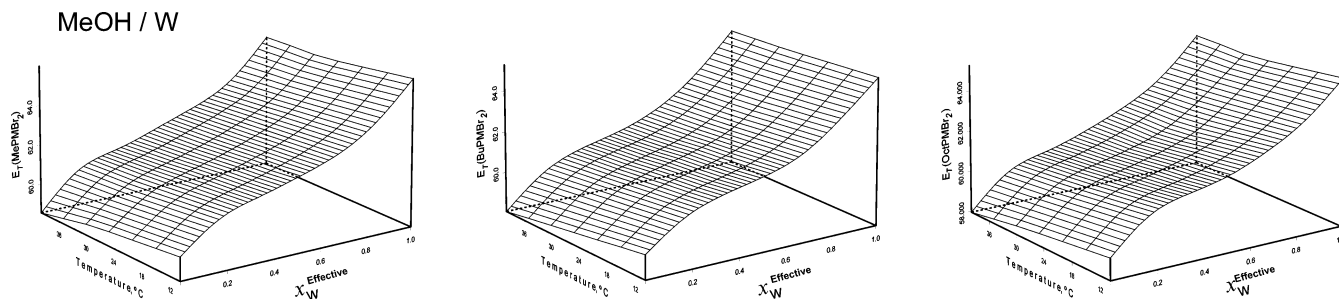


FIGURE 6. Solvent polarity/temperature/solvent composition contours for MePMBR₂, BuPMBR₂, and OcPMBR₂ in MeOH/W.

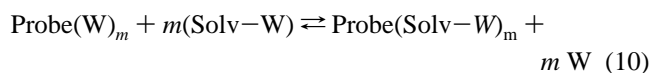
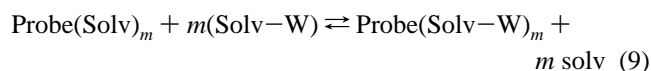
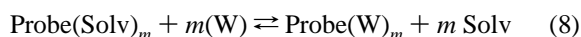
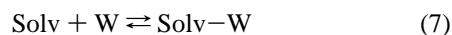
for the binary mixtures. These values are of the same magnitude as those calculated for other systems, e.g., Gibbs free energies of transfer of alkylammonium ions from water to binary solvent mixtures, at $\chi_w = 0.5$; 0.06 and 0.3 kcal/CH₂ for MeCN–W and MeOH–W, respectively;^{29,30} experimental and theoretically calculated Gibbs free energies of solvation of alkanes and *n*-chain alcohols in water, 0.18 ± 0.05 kcal/CH₂ and 0.16 ± 0.05 kcal/CH₂, respectively.³⁰ Therefore, solute–solvent hydrophobic interactions are relevant to $E_T(\text{probe})$, as argued elsewhere.^{1–5} To our knowledge, this is the first time that solvatochromic probes have been employed to obtain solvation energy/CH₂. Compared to other methods, the present one has the merit of versatility and experimental simplicity.

Thermosolvatochromism. Thermosolvatochromism of RPMBR₂ has been studied in mixtures of water with MeOH, PrOH, MeCN, and DMSO, over the whole composition range. The solvent polarity/temperature/solvent composition contours for the three indicators synthesized are shown Figure 6 for MeOH. The corresponding contours for PrOH, MeCN and DMSO are shown in Figure SI-2 in Supporting Information.

Considering these results, the following is relevant:

5. Instead of reporting extensive lists of $E_T(\text{RPMBR}_2)$ and solvent compositions, we have calculated the (polynomial) dependence of polarity on the analytical mole fraction of water and present the regression coefficients in Table SI-2 in Supporting Information. The degree of polynomial employed is that which gave the *best* data fit, as indicated by the multiple correlation coefficients, r^2 and SD. For example, the data for PrOH–W could have been conveniently adjusted with a fifth-power polynomial. The quality of our data is evidenced by these statistical criteria and by the excellent agreement between calculated and experimental $E_T(\text{RPMBR}_2)_{\text{solv}}$, at all temperatures; see Table SI-2 in Supporting Information.

6. We have treated the data obtained according to the following solvation model:^{3–5}



where m represents the number of solvent molecules whose exchange in the probe solvation coordination shell affects E_T (probe); usually $m \leq 2$ (m should not be confused with the total number of solvent molecules that solvate the probe). The use of 1:1 stoichiometry for Solv–W is a practical and convenient assumption because it renders subsequent calculations tractable; it has been extensively employed by others to describe solvatochromism.^{31,32} Mixed solvent species with stoichiometry other than 1:1 may be treated, to a good approximation, as mixtures of the 1:1 structure plus excess of a pure solvent. The relevant point about this model is that it *explicitly* considers the formation of hydrogen-bonded (or complex) solvent species Solv–W. Consequently, the mole fractions employed in all calculations (except those of Table SI-2) are “effective” not analytical ones. The equilibrium constants of eqs 8–10 are termed solvent “fractionation factors, φ ”. These are defined on the mole fraction scale, after rearrangement, as:

$$\varphi_{\text{W/Solv}} = \frac{x_{\text{W}}^{\text{Probe}}/x_{\text{Solv}}^{\text{Probe}}}{(x_{\text{W}}^{\text{Bk:Effective}}/x_{\text{Solv}}^{\text{Bk:Effective}})^m} \quad (11)$$

$$\varphi_{\text{Solv} - \text{W/Solv}} = \frac{x_{\text{Solv} - \text{W}}^{\text{Probe}}/x_{\text{Solv}}^{\text{Probe}}}{(x_{\text{Solv} - \text{W}}^{\text{Bk:Effective}}/x_{\text{Solv}}^{\text{Bk:Effective}})^m} \quad (12)$$

$$\varphi_{\text{Solv} - \text{W/W}} = \frac{x_{\text{Solv} - \text{W}}^{\text{Probe}}/x_{\text{W}}^{\text{Probe}}}{(x_{\text{Solv} - \text{W}}^{\text{Bk:Effective}}/x_{\text{W}}^{\text{Bk:Effective}})^m} \quad (13)$$

where Bk refers to bulk solvent. In eq 11, $\varphi_{\text{W/Solv}}$ describes the composition of the probe solvation coordination shell, relative to that of bulk solvent. For $\varphi_{\text{W/Solv}} > 1$, the solvation coordination shell is richer in W than bulk solvent; the converse is true for $\varphi_{\text{W/Solv}} < 1$, i.e., the probe is preferentially solvated by the organic solvent. Finally, a solvent fractionation factor of unity indicates an ideal behavior, i.e., the solvation coordination shell and bulk solvent have the same composition. The same line of reasoning applies to $\varphi_{\text{Solv} - \text{W/Solv}}$ (complex solvent displaces organic solvent) and $\varphi_{\text{Solv} - \text{W/W}}$ (complex solvent displaces W), depicted in eqs 12 and 13, respectively.

7. Results of application of eqs 11–13 are listed in Table 4. The fit of the model to our thermosolvatochromic data is shown by values of (r^2) and χ^2 and by the excellent agreement between

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TABLE 4. Analysis of Thermosolvatochromic Responses of MePMBr₂, BuPMBr₂, and OcPMBr₂ in Solvent/Water Mixtures, According to Equations 11–13

organic solvent	probe	<i>T</i> , °C	<i>m</i>	$\varphi_{W/Solv}$	$\varphi_{Solv-W/Solv}$	$\varphi_{Solv-W/W}$	$E_T(\text{probe})_{Solv}$	$E_T(\text{probe})_W$	$E_T(\text{probe})_{Solv-W}$	<i>r</i> ²	χ^2	
MeOH	MePMBr ₂	10	0.971	0.567	1.867	3.293	59.77 [± 0.04]	65.96 [± 0.04]	61.32 [± 0.2]	0.9996	0.0022	
		25	1.007	0.578	1.805	3.123	59.27 [± 0.03]	65.27 [± 0.02]	60.99 [± 0.03]	0.9999	0.0008	
		40	0.870	0.610	1.756	2.879	58.55 [± 0.04]	65.17 [± 0.03]	60.67 [± 0.21]	0.9998	0.0015	
	BuPMBr ₂	10	1.264	0.524	2.618	4.996	59.31 [± 0.04]	65.26 [± 0.04]	60.90 [± 0.13]	0.9994	0.0031	
		25	1.115	0.539	2.400	4.453	58.70 [± 0.04]	64.96 [± 0.04]	60.44 [± 0.14]	0.9997	0.0023	
		40	1.056	0.544	2.05	3.768	58.10 [± 0.05]	64.73 [± 0.05]	59.98 [± 0.22]	0.9995	0.0033	
	OcPMBr ₂	10	1.289	0.474	2.676	5.646	59.05 [± 0.03]	65.23 [± 0.03]	61.08 [± 0.07]	0.9998	0.0011	
		25	1.246	0.498	2.544	5.108	58.55 [± 0.04]	64.62 [± 0.04]	60.47 [± 0.12]	0.9996	0.0022	
		40	1.147	0.52	2.287	4.398	57.97 [± 0.05]	64.51 [± 0.04]	60.02 [± 0.16]	0.9996	0.0023	
	PrOH	MePMBr ₂	10	1.580	0.211	71.138	337.147	55.45 [± 0.06]	66.00 [± 0.08]	59.76 [± 0.11]	0.9995	0.0069
			25	1.359	0.215	32.546	151.377	54.95 [± 0.08]	65.42 [± 0.11]	58.56 [± 0.25]	0.9990	0.0133
			40	1.300	0.233	27.653	118.682	54.34 [± 0.09]	65.21 [± 0.12]	59.35 [± 0.33]	0.9990	0.0142
BuPMBr ₂		60	1.110	0.239	13.105	54.833	53.70 [± 0.10]	64.88 [± 0.13]	59.60 [± 0.70]	0.9989	0.0166	
		10	1.652	0.200	82.601	413.005	54.99 [± 0.08]	65.30 [± 0.12]	58.70 [± 0.17]	0.9988	0.0154	
		25	1.430	0.208	40.891	196.591	54.54 [± 0.09]	65.03 [± 0.13]	58.56 [± 0.26]	0.9988	0.0164	
OcPMBr ₂		40	1.341	0.229	36.227	158.197	53.99 [± 0.05]	64.79 [± 0.06]	58.14 [± 0.15]	0.9997	0.0042	
		60	1.323	0.233	32.890	141.159	53.42 [± 0.05]	64.46 [± 0.07]	57.69 [± 0.22]	0.9997	0.0049	
		10	1.696	0.185	108.880	588.541	55.08 [± 0.09]	65.30 [± 0.14]	58.31 [± 0.17]	0.9984	0.0191	
MeCN		MePMBr ₂	25	1.618	0.200	98.820	494.100	54.54 [± 0.07]	64.71 [± 0.09]	58.00 [± 0.13]	0.9992	0.0093
			40	1.512	0.219	76.662	350.055	54.02 [± 0.05]	64.53 [± 0.07]	57.82 [± 0.11]	0.9996	0.0046
			60	1.442	0.226	68.298	302.204	53.41 [± 0.05]	64.28 [± 0.07]	57.37 [± 0.12]	0.9997	0.0045
	BuPMBr ₂	10	0.994	1.461	27.076	18.533	53.52 [± 0.08]	65.99 [± 0.08]	60.14 [± 0.29]	0.9995	0.0075	
		25	1.057	1.494	26.781	17.926	53.39 [± 0.14]	65.36 [± 0.13]	59.58 [± 0.69]	0.9988	0.0199	
		40	1.015	1.527	22.579	14.787	52.93 [± 0.06]	65.21 [± 0.06]	58.90 [± 0.42]	0.9998	0.0043	
	OcPMBr ₂	60	0.978	1.578	16.844	10.674	52.53 [± 0.04]	64.85 [± 0.04]	57.67 [± 0.46]	0.9999	0.0018	
		10	1.067	1.446	30.535	21.117	53.40 [± 0.08]	65.30 [± 0.08]	59.46 [± 0.30]	0.9995	0.0077	
		25	1.064	1.450	29.756	20.521	52.94 [± 0.06]	65.00 [± 0.06]	59.02 [± 0.25]	0.9998	0.0037	
	DMSO	MePMBr ₂	40	1.064	1.481	28.452	19.211	52.60 [± 0.03]	64.75 [± 0.03]	58.48 [± 0.17]	0.9999	0.0011
			60	1.006	1.512	20.600	13.624	52.11 [± 0.05]	64.46 [± 0.05]	57.33 [± 0.45]	0.9999	0.0029
			10	1.092	1.396	41.098	29.440	53.27 [± 0.08]	65.25 [± 0.08]	59.49 [± 0.21]	0.9995	0.0072
BuPMBr ₂		25	1.140	1.405	37.621	26.777	53.05 [± 0.09]	64.73 [± 0.09]	59.08 [± 0.34]	0.9994	0.0099	
		40	1.121	1.444	35.521	24.599	52.74 [± 0.04]	64.53 [± 0.04]	58.40 [± 0.18]	0.9999	0.0016	
		60	1.050	1.489	24.088	16.177	52.34 [± 0.04]	64.27 [± 0.04]	57.13 [± 0.36]	0.9999	0.0022	
OcPMBr ₂		25	0.768	0.342	0.356	1.041	53.33 [± 0.05]	65.25 [± 0.06]	57.14 [± 7.00]	0.9999	0.0036	
		40	0.745	0.412	0.342	0.830	53.12 [± 0.03]	65.13 [± 0.06]	54.05 [± 6.70]	0.9998	0.0044	
		60	0.703	0.421	0.242	0.575	52.74 [± 0.06]	64.81 [± 0.06]	52.93 [± 8.25]	0.9998	0.0045	
BuPMBr ₂		25	0.805	0.292	0.357	1.223	52.95 [± 0.06]	64.93 [± 0.07]	57.22 [± 7.76]	0.9998	0.005	
		40	0.783	0.303	0.353	1.165	52.66 [± 0.05]	64.77 [± 0.06]	57.33 [± 8.88]	0.9998	0.004	
		60	0.756	0.400	0.348	0.870	52.46 [± 0.06]	64.43 [± 0.06]	52.60 [± 6.00]	0.9998	0.0043	
OcPMBr ₂	25	0.911	0.248	0.514	2.073	53.01 [± 0.05]	64.68 [± 0.06]	57.67 [± 13.09]	0.9998	0.0041		
	40	0.829	0.258	0.408	1.581	52.46 [± 0.06]	64.52 [± 0.04]	57.92 [± 7.02]	0.9999	0.0023		
	60	0.800	0.282	0.370	1.312	52.45 [± 0.06]	64.24 [± 0.06]	56.48 [± 7.44]	0.9998	0.0038		

experimental and calculated $E_T(\text{probe})_{\text{solvent}}$ and $E_T(\text{probe})_W$, respectively. The results of Table 4 are discussed in terms of their dependence on the structures of the probe and the solvent (at the same temperature, *T*) and on *T*, for the same probe and binary mixture. Values of *m* are close to unity and generally decrease as a function of increasing *T*. Likewise, for each probe in each solvent, all values of φ , $E_T(\text{probe})_{\text{Solv}}$ and $E_T(\text{probe})_W$ decrease as a function of increasing *T*. This probe desolvation agrees with the known effect of temperature on solvent structure due to less efficient hydrogen bonding and dipolar interactions.²⁸

8. Values of $\varphi_{W/ROH}$ are < unity, i.e., water is not efficient in displacing the alcohol from the probe solvation coordination shell (see the discussion on the significance of the magnitude of φ after eq 13). Whereas water and alcohols may solvate the probe by hydrogen bonding to its phenolate oxygen, ROH may further solvate the probe by hydrophobic interactions. The importance of the latter has been discussed above for pure solvents (eq 6) and may be further corroborated by the fact that the order observed is $\varphi_{W/MeOH} > \varphi_{W/PrOH}$, for every probe, in the temperature range investigated. That is, water displaces MeOH, a stronger acid ($pK_a = 15.5$) but less hydrophobic

solvent ($\log P = -0.77$), more efficiently than PrOH, a weaker acid ($pK_a = 16.1$) but more hydrophobic solvent ($\log P = 0.25$).³³

9. All $\varphi_{ROH-W/ROH}$ and $\varphi_{ROH-W/W}$ are greater 1, indicating that the probes are preferentially solvated by ROH–W; all $\varphi_{ROH-W/W}$ are greater than the corresponding $\varphi_{ROH-W/ROH}$, indicating the ROH–W displaces W more efficiently than ROH. Since the alcohols employed are more basic than water, we can assume that the structure of the complex species is given by $H_w-O-H \cdots O(R)H_{ROH}$, i.e., water is the hydrogen-bond donor to alcohol, so that the two hydrogen atoms marked in *italic* are the sites for hydrogen bonding with the probe phenolate oxygen. As argued elsewhere, this hydrogen bonding partially deactivates H_w toward further bonding; this deactivation is greater for more basic alcohols.^{34,35} Therefore, the efficiency of ROH–W in displacing alcohol and/or water from the solvation coordination shells does not seem to be due to a H-bonding ability better than those of the precursor solvents; it is due to hydrophobic

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TABLE 5. $\beta_{\text{statistical}}$ Coefficients of Equation 14, Applied to Solvatochromism of the Probes Synthesized in Aqueous Methanol and 1-Propanol, at 25 °C

mixture	probe	$\beta_{\text{statistical}} (s)$	$\beta_{\text{statistical}} (a)$	$\beta_{\text{statistical}} (b)$	$\beta_{\text{statistical}} (p)$	r^2
MeOH/W	MePMBR ₂	-0.94 (± 0.02)	-0.04 (± 0.01)	-0.57 (± 0.01)	-1.33 (± 0.03)	0.9999
	BuPMBR ₂	-1.25 (± 0.08)	-0.07 (± 0.02)	-0.66 (± 0.04)	-1.53 (± 0.11)	0.9999
	OcPMBR ₂	-1.29 (± 0.06)	-0.08 (± 0.02)	-0.63 (± 0.03)	-1.59 (± 0.09)	0.9999
PrOH/W	MePMBR ₂	10.52 (± 1.11)	1.13 (± 0.10)	-0.54 (± 0.16)	9.07 (± 1.03)	0.9964
	BuPMBR ₂	10.67 (± 1.22)	1.24 (± 0.12)	-0.70 (± 0.17)	9.30 (± 1.14)	0.9978
	OcPMBR ₂	13.23 (± 1.48)	1.43 (± 0.14)	-0.84 (± 0.21)	11.87 (± 1.38)	0.9936

interactions. This conclusion is corroborated by the above-discussed order of $\varphi_{\text{W/ROH}}$, and by the fact that $\varphi_{\text{PrOH-W/W}} > \varphi_{\text{MeOH-W/W}}$, for all probes, at all temperatures; see Table 4. The order $\varphi_{\text{ROH-W/W}} > \varphi_{\text{ROH-W/ROH}}$ is because $\varphi_{\text{ROH-W/W}}$ is related to the difference between hydrogen bonding plus hydrophobic interactions of ROH-W versus only hydrogen bonding by water (see eq 10). On the other hand, hydrogen bonding and hydrophobic interactions contribute to solvation by the two solvent species involved in $\varphi_{\text{ROH-W/ROH}}$ (eq 9).

10. For mixtures of water with dipolar aprotic solvents $\varphi_{\text{W/MeCN}} > 1$, whereas $\varphi_{\text{W/DMSO}} < 1$, i.e., water is more efficient in displacing MeCN than DMSO from the solvation coordination shell. MeCN can solvate positive centers better than negative ones, i.e., it interacts less with the probe phenolate oxygen, being displaced by water, because the latter is capable of solvating both types of centers effectively^{8,36}. The preceding conclusion agrees with the following result: $\varphi_{\text{MeCN-W/MeCN}} > \varphi_{\text{MeCN-W/W}}$, i.e., the complex solvent displaces MeCN from the probe solvation coordination shell more efficiently than it displaces water, in agreement with the weak interaction of MeCN with the probe phenolate oxygen.

Solvation by aqueous DMSO merits a comment: Whereas $\varphi_{\text{W/DMSO}} < 1$, i.e., similar to solvation by alcohols, values of $\varphi_{\text{DMSO-W/W}}$ and $\varphi_{\text{DMSO-W/DMSO}}$ are less than or close to unity. To our knowledge, this is the first example of a Solv-W species that is inefficient in displacing its precursor components from the probe solvation coordination shell. Consider first the exchange of the pure solvents. Values of $\varphi_{\text{W/DMSO}} < 1$ probably because the organic solvent may solvate the probe by strong dipole-dipole and hydrophobic interactions, akin to those operative in aqueous DMSO.³⁷ The small magnitudes of $\varphi_{\text{DMSO-W/W}}$ and $\varphi_{\text{DMSO-W/DMSO}}$ may be attributed to the fact that the interaction of DMSO with W attenuates the solvation efficiency of the complex solvent. Evidence showing that DMSO-W interactions are stronger than W-W interactions include theoretical calculations³⁸ IR; ¹H and ¹³C NMR,^{39,40} neutron scattering⁴¹ and electron-spray mass spectroscopy³⁷. Additionally, plot of α_{mixt} versus χ_{DMSO} shows negative deviation from linearity; the corresponding plot for β_{mixt} shows a positive deviation,⁴² i.e., aqueous DMSO is less acidic than expected. In other words, DMSO-W aggregate may be considered as a deactivated species both in hydrogen bonding

to the probe phenolate oxygen and electrostatic interaction with the probe positively charged nitrogen; this leads to the small φ observed.

11. Table 4 shows that as a function of increasing temperature, m , $E_T(\text{probe})_{\text{solv}}$, $E_T(\text{probe})_{\text{W}}$, $\varphi_{\text{Solv-W/Solv}}$, and $\varphi_{\text{Solv-W/W}}$ decrease, whereas $\varphi_{\text{W/Solv}}$ increases. The decrease in polarities of pure solvents may be attributed to a decrease of solvent stabilization of the probe ground state, as a result of the concomitant decrease of solvent structure, and hydrogen-bonding ability.^{43,44} Preferential “clustering” of water and solvents as a function of increasing temperature means that the strength of Solv-W interactions decrease in the same direction,^{27,28,45,46-48} with a concomitant decrease in its ability to displace both water and solvent. This explains the decrease of $\varphi_{\text{Solv-W/Solv}}$ and $\varphi_{\text{Solv-W/W}}$ as a function of increasing T . Plots (not shown) of $E_T(\text{probe})_{\text{Solv}}$ versus T gave straight lines whose (negative) slopes are given by $\Delta E_T(\text{probe})_{\text{Solvent}}/\text{degree}$ (cal mol⁻¹ K⁻¹). For PrOH and MeCN (for which four temperatures were investigated) the order observed is $\Delta E_T(\text{probe})_{\text{Solv}} > \Delta E_T(\text{probe})_{\text{W}}$, reflecting the greater effect of temperature on the structure of the solvent. Consequently, hydrogen bonding of water with probe ground state is less susceptible to temperature increase than that of the organic component. This leads to a measurable “depletion” of pure solvent in the probe solvation coordination shell, so that $\varphi_{\text{W/Solv}}$ increases as a function of increasing temperature;

12. The results of application of eq 6 to a single probe in a series of pure solvents raises the question whether the same approach can be applied to the solvatochromic behavior of a probe in a series of binary solvent mixtures at a fixed temperature. We used eq 14, where (more fundamental) $\text{p}K_{\text{a mixt}}$ was substituted for α_{mixt} :

$$E_T(\text{probe})_{\text{mixt}} = \text{constant} + s \pi_{\text{mixt}}^* + a \text{p}K_{\text{a mixt}} + b \beta_{\text{mixt}} + p \log P_{\text{mixt}} \quad (14)$$

This equation has been applied to aqueous MeOH and PrOH; the regression coefficients are listed in Table SI-3 in Supporting Information, whereas the $\beta_{\text{statistical}}$ values are listed in Table 5. Although the number of probes and solvents tested is small, we are satisfied with the high correlation coefficients calculated. An important result of Table 5 is the noticeable increase of $\beta_{\text{statistical}}$ of s and p as a function of increasing N_c (in the same binary mixture) and, for the same probe, on going from MeOH to PrOH. Therefore, our data indicate that hydrophobic interac-

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tions are important to solvatochromism, both in pure solvents and binary solvent mixtures.

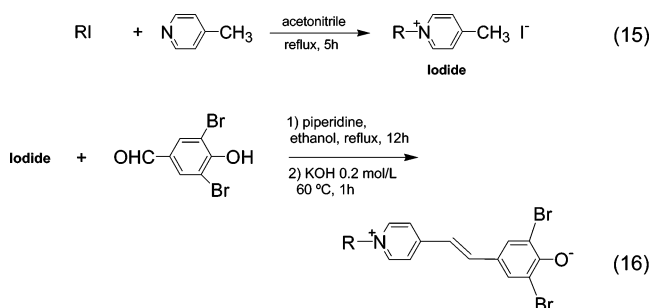
Conclusions

Solvation in pure solvents is due to interactions that depend on the properties of the solute (structure, pK_a , and hydrophobicity) and the solvent, including proton donation/acceptance, dipolarity/polarizability, and as shown here, lipophilicity. Evaluation of the relative importance of these interactions requires studying the solvatochromism of probes of adequate structure, e.g., the series $RPMBR_2$, where the pK_a is kept constant while the hydrophobic character is increased. Thermosolvatochromism in binary solvent mixtures can be described by a general mechanism, based on solvent exchange equilibria between the species present in solution (W, Solv, and Solv-W complexes, respectively) and their counterparts in the probe solvation coordination shell. The nonideal dependence of $E_T(RPMBR_2)$ on χ_w is mainly due to preferential solvation of the probe, especially by Solv-W; aqueous DMSO is an exception. Temperature effect on φ is rationalized in terms of the structures of water and solvent and their mutual interactions. Temperature increase results in a gradual desolvation of every probe (i.e., decreased stabilization of its ground-state by W, Solv, and Solv-W), in all binary mixtures; desolvation energies depend on the hydrophobicity of the probe and the solvent and are sensitive to the composition of the binary solvent mixture. The Taft-Kamlet-Abboud equation has been modified by including a solvent lipophilicity term; the modified equation applies satisfactorily to pure and binary solvent mixtures. Solvation of zwitterionic probes seems to be more sensitive to medium lipophilicity than its basicity.

Values of φ and its dependence on the components of the binary mixture and the properties of the probe, in particular its lipophilicity, may be fruitfully employed to better explain reactivity data, e.g., the (complex) dependence on medium composition of rate constants and activation parameters of different reactions, e.g., spontaneous decarboxylations,^{49–51} acid-, base-, pH-independent, and enzyme-catalyzed hydrolyses of carboxylic and carbonate esters and *N*-acylimidazoles^{52–60} and the dependence of the kinetic order with respect to water on the composition of the binary mixture^{8,61–62}

Experimental Section

Synthesis of the Probes Employed. $RPMBR_2$ were synthesized according to the following scheme:^{63–66} The synthesis of



1-alkyl-4-methylpyridinium iodides from 4-methylpyridine or *n*-alkyl iodide was carried out in MeCN, as recommended elsewhere, followed by removal of the solvent and excess alkyl iodide, eq 15.⁶³ The light yellow products were either solid, 1,4-dimethylpyridinium iodide, or liquid, other 1-alkyl-4-methylpyridinium iodides. Their purity was established by TLC analysis by using ethanol/acetic acid/chloroform eluent (1:1:18, by volume). The aldehyde 3,5-dibromo-4-hydroxybenzaldehyde was prepared by the reaction of bromine with 4-hydroxybenzaldehyde in glacial acetic acid, as given elsewhere.⁶⁷ Condensation of this aldehyde with 1-alkyl-4-methylpyridinium iodides in the presence of piperidine, eq 16, followed by treatment with KOH, and recrystallization from aqueous methanol gave $RPMBR_2$, as red crystals. Table SI-4 in Supporting Information shows the yields, melting points, elemental analyses, and relevant IR frequencies for the probes synthesized. Attributions of the 1H and ^{13}C NMR spectra are listed in Tables SI-5 and SI-6, respectively, in Supporting Information.

Spectroscopic Determination of $E_T(\text{probe})$ in Pure Solvents and in Binary Solvent Mixtures. The probes employed for studying solvatochromism and thermosolvatochromism were $MePMBR_2$, $BuPMBR_2$, and $OcPMBR_2$. Aliquots of the probe solution in acetone were pipetted into small volumetric vials, followed by evaporation of the acetone at room temperature, under reduced pressure, in the presence of P_4O_{10} . The solvent (or binary mixture) whose polarity is to be determined was added, the probe was dissolved, and the UV-vis spectrum of its solution was recorded. The following are relevant experimental data: Temperature control inside the thermostatted cellholder, ± 0.05 °C; final probe concentrations, $2-5 \times 10^{-4}$ mol/L for $MePMBR_2$, $BuPMBR_2$, and $HxPMBR_2$ and 3×10^{-5} mol/L for $OcPMBR_2$, respectively; cuvette path length, 1–4 cm; number of spectra recorded, 2 at a rate of 120 nm/min; λ_{max} calculated from the first derivative of the absorption spectrum; uncertainty in $E_T(RPMBR_2) \leq 0.15$ kcal/mol. The same procedure was repeated for binary solvent mixtures, 16 per set, prepared by weight at 25 °C. Thermosolvatochromism was studied in mixtures of water with MeOH (10–40 °C), PrOH and MeCN (10–60 °C), and DMSO (25–60 °C).

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Spectrometric Determination of the Partition Coefficient of the Probe between *n*-Octanol and Water. The aqueous phase was a phosphate buffer solution (0.05 mol/L, pH = 7.50). Equal volumes of this buffer and *n*-octanol were agitated for 1 h (tube rotator), and the phases were separated. A probe solution, 5×10^{-4} mol/L in (buffer-saturated) *n*-octanol was prepared, and its absorbance, A_{initial} , was recorded. An aliquot of this solution, V_{octanol} , was agitated with (*n*-octanol-saturated) phosphate buffer, V_{buffer} , at room temperature, for 2 h. After phase separation at 25 °C, the absorbance, $A_{\text{equilibrium}}$, of the *n*-octanol phase was measured, and the partition coefficient calculated from $\log P = \log(A_{\text{equilibrium}} \times V_{\text{buffer}} / (A_{\text{initial}} - A_{\text{equilibrium}}) V_{\text{octanol}})$. Values of $\log P$ were found to be -0.16 ± 0.01 , 1.12 ± 0.01 , and 1.86 ± 0.1 for MePMBR₂, BuPMBR₂, and HxPMBR₂, respectively.

Spectrometric Determination of the Apparent pK_a Values of the Probes. The pK_a was calculated from the Henderson–Hasselbalch equation.⁶⁸ A methanolic solution of each probe was added to potassium hydrogen phthalate buffer (0.05 mol/L) so that the final volume fraction of methanol was ≤ 0.05 and the final [probe] was $= 5 \times 10^{-4}$ mol/L. The concentrations of the zwitterionic forms were measured at 438, 443, and 440 nm for MePMBR₂, BuPMBR₂, and OcPMBR₂, respectively. At

25 °C, the apparent pK_a values of all probes were found to be 5.15 ± 0.05 .

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Supporting Information Available: Plots of $E_7(\text{OcPMBR}_2)$ versus χ_w , for different binary mixtures; solvent polarity/ temperature/solvent composition contours for MePMBR₂, BuPMBR₂, and OcPMBR₂ in binary solvent mixtures; results of the application of eq 6; polynomial dependence of $E_7(\text{RPMBR}_2)$ on the analytical mole fraction of water in the binary mixture; regression coefficients of eq 14; yields, elemental analyses, and IR frequencies of the probes synthesized; ¹H and ¹³C NMR data for the probes synthesized; calculations of the Dependence of $E_7(\text{probe})$ on the properties of the solvent; calculation of the dissociation constant of Solv–W, K_{dissoc} , $\chi_{\text{Species}}^{\text{Effective}}$, and solvent fractionation factors. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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