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NUCLEOPHILICITY OF MICELLAR SYSTEMS BASED ON AMPHIPHILIC DERIVATIVES OF 2-(OXIMINOMETHYL)IMIDAZOLE IN THE DECOMPOSITION OF 4-NITROPHENYL DIETHYL PHOSPHATE

I. V. Kapitanov

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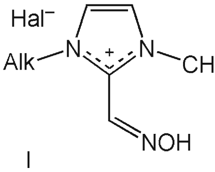
The differences in the acid–base properties and nucleophilic reactivity within a series of 1-methyl-3-alkyl-2-(oximinomethyl)imidazolium halides in the dissociation of 4-nitrophenyl diethyl phosphate were analyzed. The positive deviation of points for comicellar systems derived from compounds of this series from the Brønsted plot was shown to be related to a decrease in the values of pK_a^{app} *of the oximate fragment of the functional surfactants due to the action of the added cationic codetergent (CTAB).*

Key words: *2-(oximinomethyl)imidazole derivatives, nucleophilicity, basicity, micellar effects, functional surfactants, acyl group transfer reactions.*

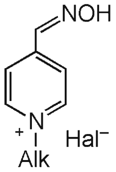
Micellar systems derived from amphiphilic supernucleophilic reagents provide for the efficient dissociation of acyl-containing ecotoxicants such as esters and anhydrides of phosphorus and sulfur acids [1, 2].

Micelle-forming derivatives of 2-(oximinomethyl)imidazole are a promising class of such reagents [3, 4]: systems with such compounds not only combine high nucleophilicity and, as a rule, a high capacity to solubilize rather hydrophobic acyl-containing ecotoxicants with correspondingly low water solubility but also permit carrying out dissociation reactions under mild conditions at pH ≈ 9.0-9.5 [3].



I

Ia (Alk = CH_3; $Hal^- = I^-$)
Ib (Alk = C_2H_5; $Hal^- = I^-$)
Ic (Alk = CH_2Ph; $Hal^- = I^-$)
Id (Alk = $C_{12}H_{25}$; $Hal^- = Br^-$)
Ie (Alk = $C_{14}H_{29}$; $Hal^- = Br^-$)
If (Alk = $C_{16}H_{33}$; $Hal^- = Br^-$)



II

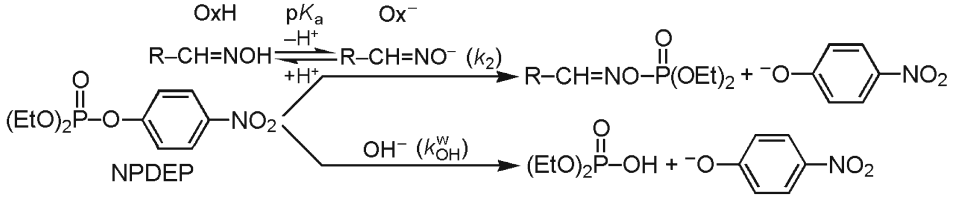
IIa (Alk = CH_3; $Hal^- = I^-$)
IIb (Alk = $C_{16}H_{33}$; $Hal^- = Br^-$)

Data previously obtained on the nucleophilicity of 1,3-dimethyl-2-(oximinomethyl)imidazolium iodide (Ia) and 1-methyl-3-hexadecyl-2-(oximinomethyl)imidazolium bromide (If) [3] and a comparison of these results with the reactivity of pyridinium derivatives IIa and IIb with similar basicity [5] in the dissociation of 4-nitrophenyl esters of diethylphosphonic acid (NPDEPS), diethyl phosphoric acid (NPDEP), and 4-toluenesulfonic acid (NPTS) showed that points for micelle-forming bromide If have significant positive deviations, while no such deviations are found for the methyl analog Ia (Fig. 1) [3, 6].

L. M. Litvinenko Institute of Physical Organic and Coal Chemistry, National Academy of Sciences of Ukraine, Vul. R. Luxemburg, 70, Donets'k 83114, Ukraine. E-mail: ivkapitanov@gmail.com. Translated from Teoreticheskaya i Éksperimental'naya Khimiya, Vol. 47, No. 5, pp. 302-308, September-October, 2011. Original article submitted July 27, 2011; revision submitted October 4, 2011.

In order to establish the reasons for the anomalously high reactivity of If, we studied and analyzed the changes in the acid–base properties and nucleophilicity of a series of imidazolium salts Ib-Ie and also their comicellar systems with cetyltrimethylammonium bromide (CTAB) in the dissociation of NPDEP.

The dissociation of NPDEP in solutions of Ia-If is given by two parallel pathways, namely, reaction with the corresponding oximate ion and alkaline hydrolysis:



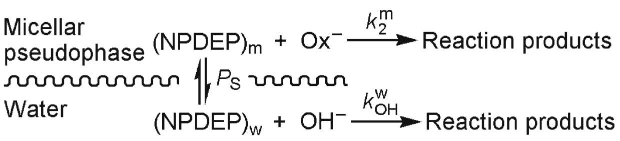
(1)

The experimental data obtained in a study of the reactivity of nonmicellar oximes Ia-Ic were treated using the equation

$$k_{\mathrm{obs}} = k^{\mathrm{w}}_{\mathrm{OH^-}}\, a_{\mathrm{OH^-}} + k^{\mathrm{w}}_{2}\,[\mathrm{OxH}]_0 \frac{K_{\mathrm{a}}}{K_{\mathrm{a}} + a_{\mathrm{H^+}}} \tag{2}$$

where k_{obs} is the observed reaction rate constant, $\mathrm{s^{-1}}$, $k^{\mathrm{w}}_{\mathrm{OH^-}}\, a_{\mathrm{OH^-}}$ corresponds to the contribution of alkaline hydrolysis, k^{w}_{2} is the second-order rate constant characterizing the nucleophilicity of the corresponding oximate ion, L/mol·s, $[\mathrm{OxH}]_0$ is the analytical oxime concentration, mol/L, K_{a} is the rate constant for its acid ionization, and $a_{\mathrm{H^+}}$ is the hydrogen ion activity [3, 5, 6].

In the case of functional surfactants Id-If and their comicellar systems with CTAB, the dissociation involves distribution of the substrate between water and the micellar pseudophase with distribution coefficient P_{S}:



(3)

The kinetic behavior of the functional surfactants and their comicelles with CTAB is described in the framework of the pseudophase distribution model:

$$k_{\mathrm{obs}} = \frac{\chi (k^{\mathrm{m}}_{2}/V_{\mathrm{m}}) K_{\mathrm{S}} C + k^{\mathrm{w}}_{\mathrm{OH^-}}\, a_{\mathrm{OH^-}}}{1 + K_{\mathrm{S}} C} \frac{K^{\mathrm{app}}_{\mathrm{a}}}{K^{\mathrm{app}}_{\mathrm{a}} + a_{\mathrm{H^+}}} \tag{4}$$

where χ is the mole fraction of the functional surfactant in the comicelle with CTAB, k^{m}_{2} is the second-order rate constant characterizing the nucleophilicity of the oximate fragment, L/mol·s, V_{m} is the partial mole volume of the surfactant, L/mol, C is the concentration of the micellarized detergent, mol/L ($C = C_0$ – CMC), CMC is the critical micelle concentration, $K_{\mathrm{S}} \approx (P_{\mathrm{S}} - 1)V_{\mathrm{m}}$ is the substrate binding equilibrium constant, L/mol, and $K^{\mathrm{app}}_{\mathrm{a}}$ is the apparent acid ionization constant of the functional fragment of the surfactant [3, 5, 7, 8].

The observed positive deviations in reactivity and rather low value of $\mathrm{p}K^{\mathrm{app}}_{\mathrm{a}}$ for If may be attributed to a number of reasons: 1) change in the electronic effects of the substituent upon replacing the CH_3 group by a $C_{16}H_{33}$ group, 2) micelle formation, and 3) the effect of added CTAB (the reactivity of If was studied in the presence of a codetergent due to its insufficient solubility in water).

In order to determine the extent of the effect of factor 1, we obtained and studied Ib and Ic, in which the electronic effects of the Alk substituents differ somewhat from the effects of the CH_3 group in Ia [9]. The differences in the substituent

TABLE 1. Acid–Base Properties (pK_a) of Halides Ia-If at 25 °C

Compound	Spectrophotometric method	Compound	Spectrophotometric method		Kinetic method	
			$\chi \approx 0.1$ (above CMC)	$\chi = 1.0$ (below CMC)	$\chi = 0.125$ (above CMC)	$\chi = 1.0$ (above CMC)
Ia	8.35 ± 0.06	Id	7.93 ± 0.06	8.48 ± 0.06	7.8 ± 0.1	8.4 ± 0.1
Ib	8.38 ± 0.06	Ie	7.77 ± 0.06	8.53 ± 0.06	7.8 ± 0.1	8.4 ± 0.1
Ic	8.26 ± 0.06	If	7.74 ± 0.06	–	7.8 ± 0.1	–

Notes. pK_a values of Ia-Ic determined in 1 M KCl and of Id-If in 0.01 M borate buffer with 5 vol.% ethanol. The value of χ corresponds to the mole fraction of the functional surfactant in the comicelles with CTAB. In the spectrophotometric determination of pK_a for Ia-Ic, their concentration in solution was $2\cdot10^{-4}$ mol/L; for comicelles (Id-If)/CTAB, the concentration was $1.1\cdot10^{-3}$ mol/L (in 1 : 10 mole ratio, $\chi \approx 0.1$); for solutions of Id and Ie, the concentration was $1.0\cdot10^{-4}$ and $2.5\cdot10^{-5}$ mol/L, respectively. In the kinetic determination of pK_a for Id-If, the total detergent concentration was 0.01 mol/L with NPDEP as the substrate. The pK_a value for If in the absence of added CTAB could not be determined due to its low water solubility. The data for spectrophotometric determination of the pK_a values of Ia and If were taken from our previous work [3].

TABLE 2. Reactivity (k_2) for Salts Ia-If in the Dissociation of NPDEP and Physicochemical Properties (K_S and CMC) of Micellar and Comicellar Systems with Id-If at 25 °C

Compound	k_2^w, L/mol·s	Compound	χ	k_2^m/V_m, s^{-1}	k_2^m, L/mol·s	K_S, L/mol	CMC, mol/L
Ia	$(8.2 \pm 0.5)\cdot10^{-3}$	Id	1.0	$(4.4 \pm 0.5)\cdot10^{-2}$ $\{(4.3 \pm 0.4)\cdot10^{-2}\}$	0.018 {0.017}	55 ± 7	$(1.1 \pm 0.1)\cdot10^{-3}$
			0.125	$(3.6 \pm 0.4)\cdot10^{-2}$ $\{(3.4 \pm 0.4)\cdot10^{-2}\}$	0.014 {0.014}	170 ± 30	$(2.5 \pm 0.4)\cdot10^{-4}$
Ib	$(7.7 \pm 0.5)\cdot10^{-3}$	Ie	1.0	$(3.9 \pm 0.3)\cdot10^{-2}$ $\{(4.3 \pm 0.4)\cdot10^{-2}\}$	0.016 {0.017}	100 ± 15	$(3.5 \pm 0.4)\cdot10^{-4}$
			0.125	$(3.5 \pm 0.4)\cdot10^{-2}$ $\{(3.5 \pm 0.4)\cdot10^{-2}\}$	0.014 {0.014}	180 ± 25	$(2.5 \pm 0.4)\cdot10^{-4}$
Ic	$(1.1 \pm 0.1)\cdot10^{-2}$	If	1.0	—	—	—	—
			0.125	$(3.7 \pm 0.4)\cdot10^{-2}$ $\{(3.8 \pm 0.4)\cdot10^{-2}\}$	0.015 {0.015}	180 ± 30	$(2.5 \pm 0.4)\cdot10^{-4}$

Notes. The reactivity of salts Ia-Ic was studied in 1 M KCl, while the reactivity of Id-If was studied in 0.01 M borate buffer with 5 vol.% ethanol. The value of χ corresponds to the mole fraction of the functional surfactant in comicelles with CTAB. The values in curly brackets correspond to results obtained from treatment of the pH dependence plots; the other values were calculated using the concentration dependence plots. The value of V_m in calculating k_2^m was taken equal to 0.4 L/mol [3]. The rate constant for alkaline hydrolysis of NPDEP in water is 0.0096 L/mol·s [7].

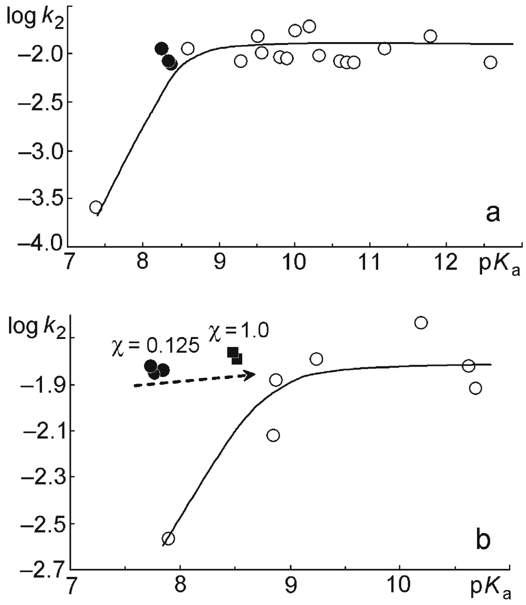


Fig. 1. Brønsted plot for the reaction of various oximes with NPDEP: a) non-micelle-forming oximes (filled circles for Ia-Ic), 1 M KCl, 25 °C, b) functional surfactants containing the oximate fragment (filled circles for Id-If), 0.01 M borate buffer, 25 °C.

electronic effects were found to have hardly any effect on the value of pK_a (Table 1) and the nucleophilicity (k_2^w, Table 2) of oximes Ib and Ic in the dissociation of NPDEP, while the points for these compounds fall on the Brønsted plot for the non-micelle-forming oximes (Fig. 1a). Hence, replacement of the CH_3 group by a $C_{16}H_{33}$ group cannot account for the significant changes in the acid–base properties of the oximate fragment.

Since the low solubility of If in water does not permit us to study its acid–base properties without the introduction of added codetergent (CTAB), we studied functional surfactants Id and Ie as structural analogs of If. On one hand, significantly improved solubility in water could be achieved by decreasing the length of the alkyl chain in these compounds and, on the other, variation of the length of the alkyl substituent permits us to follow the effect of the hydrophobic properties of the functional surfactants on their micellar behavior during the dissociation of NPDEP.

The study of the pH dependence plots* (Fig. 2a) for Id and Ie and treatment of the experimental data using Eq. (4) showed that, within experimental error, their pK_a^{app} values at χ = 1.0 were the same as for the pK_a values of non-micelle-forming analogs Ia-Ic (see Table 1). The pH dependence plots were obtained under experimental conditions providing for determination of pK_a^{app} values above the CMC (Fig. 2b,c and Table 2).

The spectrophotometric pK_a^{app} values for Id and Ie (under conditions below the CMC without added CTAB) were the same within experimental error as the values calculated from the kinetic data and only slightly higher than the pK_a values of non-micelle-forming analogs Ia-Ic (Table 1). These findings indicate that micelle formation has hardly any effect on the pK_a^{app} value of the functional fragment. A study of the acid–base properties of the comicellar systems (Id-If)/CTAB by a spectrophotometric method ($\chi \approx 0.1$, above CMC, Fig. 2d) and by a kinetic method ($\chi = 0.125$, above CMC, Fig. 2e) showed

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*Only the upper segment of the pH dependence plot was obtained for functional surfactant Ie since this salt settles as a precipitate in the absence of codetergent at pH < 8.4.

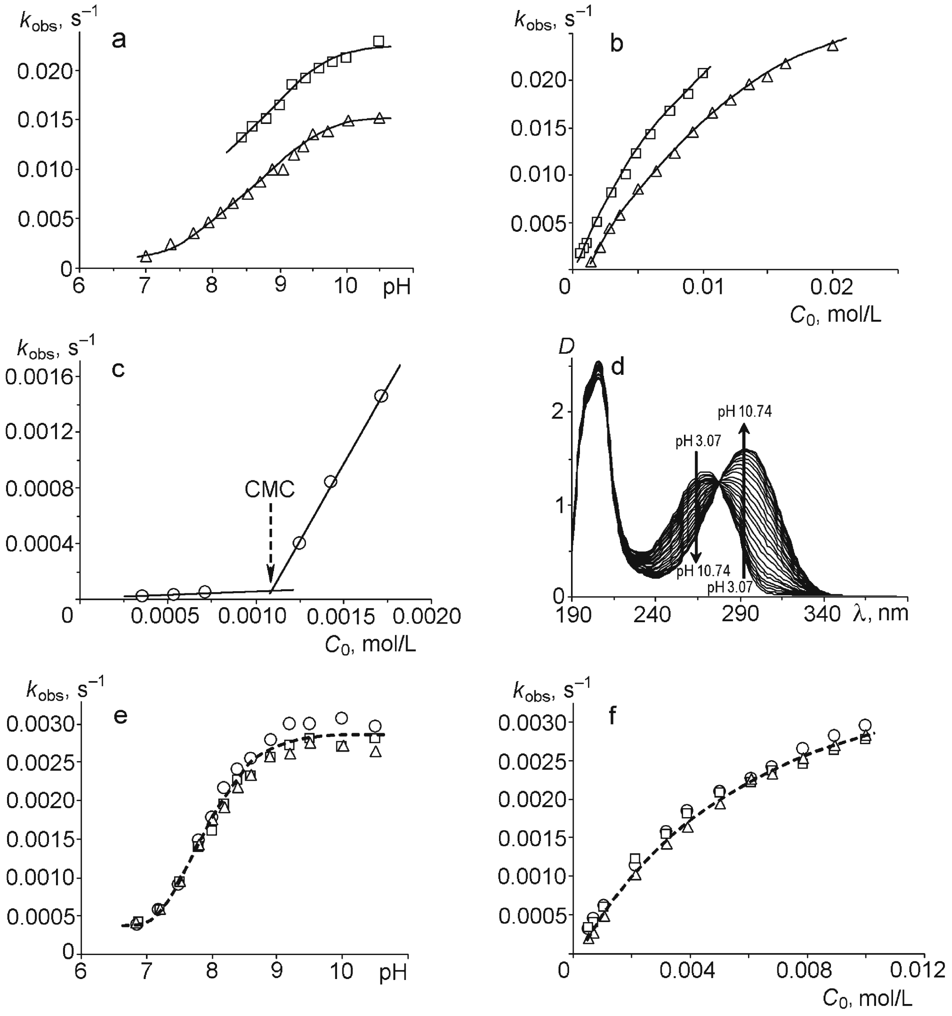

Fig. 2. Properties of functional surfactants (Id-If) and comicellar systems (Id-If)/CTAB in 0.01 M borate buffer at 25 °C: a) pH dependence for the dissociation of NPDEP by micelles of Id (Δ) and Ie (□), C_0 = 0.01 mol/L, χ = 1.0, b) concentration dependence for the dissociation of NPDEP by micelles of Id (Δ) and Ie (□), pH 10.50, χ = 1.0, c) kinetic determination of the critical micelle concentration (CMC) of functional surfactant Id, pH 10.50, χ = 1.0, d) spectrophotometric determination of pK_a^{app} of functional surfactant Id in comicelles with CTAB, $C_0 = 1.1 \cdot 10^{-3}$ mol/L, $\chi \approx 0.1$, e) pH dependence for the dissociation of NPDEP by comicelles Id/CTAB (□), Ie/CTAB (Δ) and If/CTAB (○), C_0 = 0.01 mol/L, χ = 0.125, f) concentration dependence for the dissociation of NPDEP by comicelles Id/CTAB (□), Ie/CTAB (Δ) and If/CTAB (○), pH 10.50, χ = 0.125.

(Table 1) that the pK_a^{app} values obtained are virtually independent of the alkyl chain length and about 0.6 pK_a units below the values obtained for micelles of functional surfactants with χ = 1.0, i.e., without added CTAB.

The lower values of pK_a^{app} of the oximate fragment of the functional surfactants in comicelles with CTAB are, in all likelihood, related to the electrostatic effect of the micelle surface charge. In the case of a small fraction of functional detergent, the charge arises mainly due to CTAB and, as a consequence, is positive. The positively-charged surface should facilitate dissociation of the functional fragment of the surfactant since the resultant formally electroneutral zwitter-ion is less repulsed by micelle surface.

On the other hand, comparison of the nucleophilic reactivities of Ia-Ic and Id-If (Table 2) shows that transferring the reaction to the micellar pseudophase is accompanied by an increase in the nucleophilicity of the oximate fragment by a factor of 1.5-2.0.

Decreasing the length of the alkyl substituent has virtually no effect on the nucleophilicity of the functional surfactants but has a significant effect on the efficiency of substrate binding and critical micelle concentrations (compare K_S and CMC for Id and Ie for $\chi = 1.0$ in Table 2), which, as a result, is reflected in the observed micellar effects (Fig. 2a,b).

The nucleophilic reactivity of the oximate fragment of the surfactants in the comicellar systems (Id-If)/CTAB, determined both from the pH dependence plots (Fig. 2e) and concentration dependence plots (Fig. 2f), is also virtually independent of the alkyl substituent length and is close to the nucleophilicity of the oximate fragment in the micellar systems without codetergent (Table 2). Table 2 shows similar efficiency of substrate binding and CMC values for systems (Id-If)/CTAB, leading to similar micellar effects and, as a result, identical concentration and pH profiles (Fig. 2e,f).

Hence, the major reason for the observed deviation of the points of If from the Brønsted plot for functional surfactants containing an oximate fragment is the decrease in the value of K_a^{app} of If (similar to Id and Ie) by the action of the CTAB additive. If we take the values of K_a^{app} for these compounds determined in micelles without CTAB, the deviations from the plot will be much less significant (Fig. 1b).

The reasons established for the positive deviation of the nucleophilic reactivity of comicellar systems (Id-If)/CTAB permit us to control the rate and optimal pH for carrying out the dissociation of acyl-containing ecotoxicants by variation of the content of the functional surfactant/CTAB comicelles. This permits us to obtain systems with similar micellar effects under relatively mild conditions.

EXPERIMENTAL

Salts Ib-Ie were prepared by procedures analogous to the methods described in our previous work [3]. The ^{1}H NMR spectra were taken in DMSO-d_6 on a Bruker Avance II 400 spectrometer at 400 MHz with TMS as the internal standard. The thin layer chromatography on silica gel was carried out on Merck SilicaGel 60 F_{254} plates with 10 : 1 chloroform–methanol as the eluent and development in UV light.

1-Methyl-3-ethyl-2-(oximinomethyl)imidazolium iodide (1b) was obtained in 75% yield, mp 161-162 °C (dec.). R_f 0.05. ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 1.35 (3H, t, $J = 7.2$, CH_3), 3.90 (3H, s, CH_3), 4.33 (2H, q, $J = 7.2$, CH_2), 7.79 (1H, d, $J = 2.0$, CH arom), 7.86 (1H, d, $J = 2.0$, CH arom), 8.52 (1H, s, CH=N), 13.07 (1H, s, N—OH). Found, %: C, 29.89; H, 4.28; N, 15.00. Calculated for $C_7H_{12}IN_3O$, %: C, 29.91; H, 4.30; N, 14.95.

1-Methyl-3-benzyl-2-(oximinomethyl)imidazolium iodide (Ic) was obtained in 85% yield, mp 182-183 °C (lit. for *E*-form 183-185 °C [10]), R_f 0.10. ^{1}H NMR spectrum, δ, ppm: 3.94 (3H, s, CH_3), 5.63 (2H, s, CH_2), 7.22-7.43 (5H, m, Ph), 7.86 (1H, s, CH arom), 7.93 (1H, s, CH arom), 8.58 (1H, s, CH=N), 13.04 (1H, s, N—OH). Found, %: C, 42.02; H, 4.10; N, 12.27. Calculated for $C_{12}H_{14}IN_3O$, %: C, 42.00; H, 4.11; N, 12.24.

1-Methyl-3-dodecyl-2-(oximinomethyl)imidazolium bromide (Id) was obtained in 65% yield, mp 162-163 °C, R_f 0.10. ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 0.84 (3H, t, $J = 6.8$, CH_3), 1.18-1.31 (18H, m, $(CH_2)_9$), 1.65-1.76 (2H, m, CH_2), 3.91 (3H, s, CH_3), 4.30 (2H, t, $J = 7.3$, CH_2N^+), 7.86 (1H, s, CH arom), 7.90 (1H, s, CH arom), 8.55 (1H, s, CH=N), 13.00 (1H, s, N—OH). Found, %: C, 54.51; H, 8.63; N, 11.19. Calculated for $C_{17}H_{32}BrN_3O$, %: C, 54.54; H, 8.62; N, 11.22.

1-Methyl-3-tetradecyl-2-(oximinomethyl)imidazolium bromide (Ie) was obtained in 60% yield, mp 175-176 °C, R_f 0.10. ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 0.84 (3H, t, $J = 6.8$, CH_3), 1.18-1.31 (22H, m, $(CH_2)_{11}$), 1.65-1.77 (2H, m, CH_2), 3.90 (3H, s, CH_3), 4.29 (2H, t, $J = 7.3$, CH_2N^+), 7.81 (1H, s, CH arom), 7.86 (1H, s, CH arom), 8.53 (1H, s, CH=N), 13.03 (1H, s, N—OH). Found, %: C, 56.69; H, 9.05; N, 10.42. Calculated for $C_{19}H_{36}BrN_3O$, %: C, 56.71; H, 9.02; N, 10.44.

In addition, the structure of the compounds synthesized was confirmed by IR spectroscopy. These spectra were taken in Vaseline mull on a Perkin-Elmer Spectrum BX spectrometer.

As found for Ia and If in our previous work [3], Ib-Ie have a single configuration as shown by ^{1}H NMR spectroscopy. Analysis of the literature data [10-14] also permits identification of the *E* configuration of the oximate fragment in Ia-If.

We used a sample of NPDEP with ≥95% purity supplied by Aldrich and analytically-pure and special-purity inorganic reagents without further purification. A sample of CTAB with ≥99% purity supplied by Sigma was recrystallized from acetone–methanol mixture. Doubly distilled water was used for preparing the solutions.

The kinetics of the dissociation of NPDEP was studied using a Genesys 10S UV-Vis spectrophotometer manufactured by Thermo Electron Corp. relative to the accumulation of one of the reaction products, namely, the 4-nitrophenolate ion at 25 °C and 420 nm. A Metrohm 744 pH-meter manufactured in Switzerland was used to measure pH.

The procedure for the kinetic experiments, spectrophotometric determination of pK_a, and calculation of the pseudo-first-order rate constants (k_{obs}, s^{-1}) was given by various authors [6-8, 14, 15].

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