

# Reaction of Carboxylic Acid Esters with Phenolates in Oil-in-Water Microemulsions Based on Cetyltrimethylammonium Bromide

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**Abstract**—A kinetic study of reactions of carboxylic acid esters with phenols activated with alkalis or amines in microemulsions based on cationic surfactants showed that the phenolates formed upon activation exhibit different nucleophilicity depending on the value of the negative charge on the oxygen atom, which is determined by the properties of the phenol, ionizing agent, and solvent.

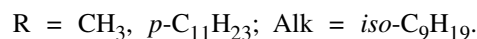
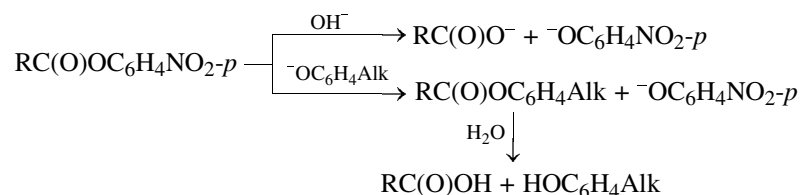
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Microemulsions are effectively used as reaction media for many chemical processes [1–3], thanks to the high solubilizing power and extremely developed phase boundary surface, providing contact between substances localized in different phases. Reagents introduced into a microemulsion, depending on their properties, can localize in different regions of the system, which can determine the reaction rate and in some cases, also the reaction mechanism and pathway [4–6].

In this study we examined the specific features of

microemulsions based on cationic surfactants as a medium for the reactions of carboxylic acid esters with phenols activated with alkalis or amines. We studied the kinetics of phenolysis of *p*-nitrophenyl acetate and *p*-nitrophenyl laurate in an oil-in-water microemulsion consisting of cetyltrimethylammonium bromide, water, *n*-butanol, and *n*-hexane.

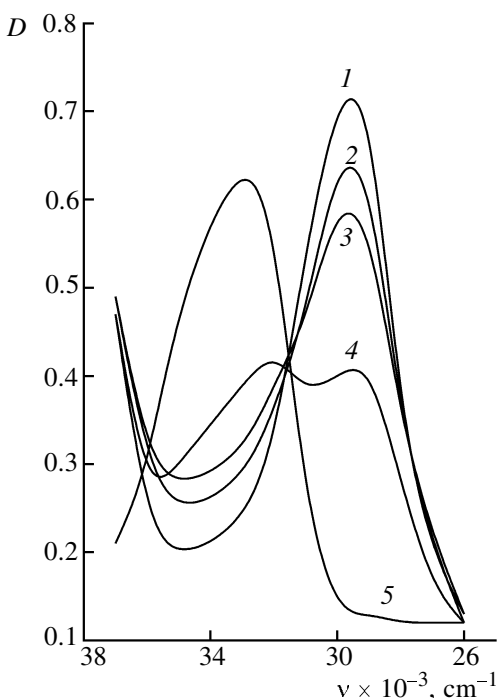
*p*-Nitrophenyl esters of carboxylic acids react with phenols in alkaline media, with nucleophilic replacement of the phenolic residue [7, 8], occurring concurrently with base hydrolysis:



The relative contributions of these two pathways to the observed rate constant in detergent microemulsions are determined by the concentration and activity of the nucleophilic species (hydroxide and phenolate anions) and by the solvent effect on each pathway. The activity of phenolates is determined by the value

of the negative charge on the oxygen atom, which can vary with ionizing agent.

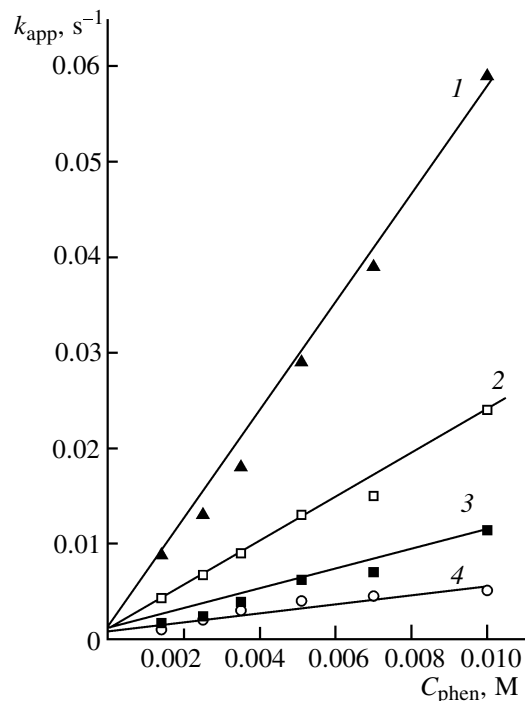
Before discussing the kinetic data, it should be noted that addition of cetyltrimethylammonium bromide gives rise to a positive charge on the phase



**Fig. 1.** Absorption spectra of 4-isononylphenol in a microemulsion based on cetyltrimethylammonium bromide at pH (1) 13.0, (2) 11.4, (3) 11.1, (4) 10.5, and (5) 3.0.

boundary surface in microemulsions; as a result, the anions present in the system are concentrated in the Stern layer. This, in turn, leads to a shift of acid–base equilibria involving phenols and to changes in the concentration of hydroxide ions formed by partial hydrolysis of phenolates.

In this study we examined the acid–base properties of phenols by UV spectroscopy according to [9]. The high molar extinction coefficients of phenols allow them to be examined at low concentrations, so that it becomes possible to determine  $pK_a$  for sparingly soluble substances. Furthermore, whereas potentiometric titration requires substance concentrations exceeding 0.005 M, at which the solubilization of negatively charged species may cause a significant decrease in the surface charge density of the emulsion microdroplets, at low concentrations this effect is avoided. From the absorption of the phenolate form at various pH values, we calculated the apparent  $pK_a$  value ( $pK_{a,app}$ ) by the Henderson–Hasselbach equation [9]  $pK_{a,app} = pH + \log([phenol]/[phenolate])$ . The effect of pH on the absorption spectrum of an alkylphenol in a microemulsion based on cetyltrimethylammonium bromide is illustrated by Fig. 1; the  $pK_a$  values of phenol and isononylphenol are 9.92 and 10.49, respectively.



**Fig. 2.** Apparent rate constant of phenolysis of esters as a function of the concentration of sodium alkylphenolate in the aqueous phase of an oil-in-water microemulsion based on cetyltrimethylammonium bromide ( $\phi$  0.74, 25°C): (1) acetate I + 4-isononylphenolate, (2) acetate I + phenolate, (3) laurate II + 4-isononylphenolate, and (4) laurate II + phenolate.

The kinetic data characterizing the reaction of *p*-nitrophenyl acetate I and *p*-nitrophenyl laurate II with phenolates in an oil-in-water microemulsion based on cetyltrimethylammonium bromide are given in Fig. 2 and below. The portion intercepted on the ordinate by the plot of the observed rate constant  $k_{app}$  vs. phenolate concentration corresponds to the rate constant of base hydrolysis  $k_0$  (Fig. 2). This quantity is low, but it should be taken into account, especially at low phenolate concentrations. The linearity of the concentration dependence allows us to evaluate the second-order rate constants of phenolysis  $k_2$  by the relationship  $k_2 = (k_{app} - k_0)/C_{phen}$ . The results are given below. For the reaction of unsubstituted phenol with acetate I,  $k_2$  in the examined microemulsion is approximately two times higher than in water [8], which may be due to concentration of phenolate at the positively charged microdroplet surface with the substrate solubilized in the surface layer.

Nucleophile	$k_2$ (acetate) $l\text{mol}^{-1}\text{s}^{-1}$	$k_2$ (laurate) $l\text{mol}^{-1}\text{s}^{-1}$
Sodium phenolate	2.4	0.5
Sodium 4-isononylphenolate	5.8	1.14

**Table 1.** Rate constants of cleavage of esters in an oil-in-water microemulsion based on cetyltrimethylammonium bromide (water volume fraction 0.74) at 25°C

System	$C_{IP}^a$ , M	pH	Acetate I		Laurate II	
			$k_0$ , s <sup>-1</sup>	$k_{app}$ , s <sup>-1</sup>	$k_0$ , s <sup>-1</sup>	$k_{app}$ , s <sup>-1</sup>
Phenol + triethylamine	0.0125	10.10	0.0050	0.0145	0.0016	0.0026
	0.025	10.15	0.0055	0.0237	0.0019	0.0036
	0.0375	10.20	0.0060	0.0366	0.0021	0.00608
	0.050	10.25	0.0065	0.0448	0.0030	0.0076
4-Isononylphenol + triethylamine	0.0083	11.02	0.0105	0.0117	0.0030	0.00319
	0.0125	11.2	0.018	0.0202	0.0041	0.00388
	0.025	11.3	0.021	0.0261	0.0062	0.00607
	0.050	11.35	0.040	0.0454	0.0095	0.00994
Phenol + methyldi( <i>n</i> -octyl)amine	0.025	8.10	0.0014	0.00085	0.00005	0.000054
	0.050	8.00	0.0012	0.00096	0.00005	0.000124
4-Isononylphenol + methyldi( <i>n</i> -octyl)amine	0.025	8.10	0.0014	0.000097	0.00005	0.00003
	0.050	8.05	0.0013	0.00011		
Phenol + methylmorpholine	0.0025	8.65	0.0007	0.0013	–	–
	0.050	8.75	0.0008	0.0018		

<sup>a</sup> ( $C_{IP}$ ) Ion pair concentration.

When comparing the nucleophilic activities of unsubstituted phenolate and isopropylphenolate, we should take into account their different distribution in microemulsions. The polarity of the microenvironment of isononylphenolate localized in the interface layer or near it in the oil phase is lower compared to phenolate which is concentrated in water. The decreased polarity of the reaction zone should lead to deceleration of  $S_N2$  reactions such as phenolysis of carboxylic acid esters. However, actually isononylphenolate anion in microemulsions is two–three times more active than phenolate anion. This trend may be due to the fact that the nucleophile and substrate are concentrated in the same region of microemulsions. Hence, in the case of isononylphenolate the positive concentration effect, underlying the catalytic effect of highly organized media, prevails over the negative effect of the medium.

In this study, not only alkalis but also various alkylamines were used for ionization of alkylphenols. Phenol–amine complexes form ion pairs  $ArOH \cdot NR_3 = ArO^- + HNR_3^+$ , with the electron density on the nucleophilic center depending on the ratio of  $pK_a$  of the reaction participants: The lower  $pK_a$  of phenols and the higher  $pK_a$  of protonated amines, the higher the electron density [10, 11]. Also, in microheterogeneous systems one of decisive conditions of ion pair formation is localization of the proton-donor and acceptor compounds in the same phase. These factors are reflected in the reactivity of phenolates in cleavage of

esters. To eliminate additional complications and the possibility of aminolysis, we used tertiary amines only. Also, in separate experiments we found that the contribution of the hydrolysis catalyzed by the amines (general base catalysis) was negligible. The contribution of base hydrolysis (characterized by constant  $k_0$ ) to the observed rate constant was taken into account by determining  $k_0$  in separate experiments at the same pH as in the systems with amines.

The kinetic data for the reactions of *p*-nitrophenyl esters of carboxylic acids with phenols in the presence of amines and the  $pK_a$  values of these compounds in a direct microemulsion based on cetyltrimethylammonium bromide are given in Tables 1 and 2. These data show that, if both components of a pair are hydrophilic and are localized in the aqueous phase and if the difference between their  $pK_a$  values is large, the phenol in the arising intermolecular complex can acquire pronounced nucleophilic properties. In particular, with unsubstituted phenol and highly basic triethylamine,  $k_{app}$  is considerably higher than  $k_0$  with both acetate I and laurate II. The second-order rate constants characterizing the reactivity of this ion pair (l mol<sup>-1</sup> s<sup>-1</sup>) are 0.75 for acetate and 0.09 for laurate, i.e., they are three–five times lower compared to sodium phenolate in the same microemulsion.

If a phenol is hydrophobic (4-isononylphenol) and an amine is strongly basic (high  $pK_a$ ) and readily soluble in water (triethylamine), no ion pair is formed. The amine creates high pH in the aqueous phase of

**Table 2.**  $pK_a$  values of amines and second-order rate constants of the reaction of acetate **I** with phenol activated by tertiary amines in a microemulsion based on cetyltrimethylammonium bromide (volume fraction of water 0.74, 25°C)

Amine no.	Amine	$pK_a$ (water)	$pK_a$ (microemulsion)	$k_2$ (phenolysis), $l\ mol^{-1}\ s^{-1}$
1	Triethylamine	10.7	10.65	0.77
2	2-Diethylethanolamine	9.9	9.85	0.368
3	3-Dimethylaminopropanol	10.1	9.50	0.306
4	Dimethylbenzylamine	8.9	8.20	0.090
5	<i>N</i> -Methyldiethanolamine	8.6	8.80	0.204
6	<i>N</i> -Methylmorpholine	7.4	7.85	0.002
7	<i>N</i> -Heptylpiperidine	10.0	8.12	0.098
8	Methyldi( <i>n</i> -octyl)amine <sup>a</sup>	–	6.85	0

<sup>a</sup>  $pK_a$  in water was not determined because of the low solubility of the amine in water.

the microemulsion, and the apparent rate constant corresponds to the base hydrolysis (Table 1).

Weakly basic hydrophilic amines should not induce significant charge separation in complexes with phenols, and hydrolysis of the substrate is the predominant process irrespective of the structure of the phenol. This is the case with methylmorpholine: With both *p*-nitrophenyl esters,  $k_{app}$  coincides with  $k_0$ , suggesting insignificant contribution of phenolysis to the overall process.

The second-order rate constants of phenolysis of acetate **I** under the action of the phenol–amine ion pair and the  $pK_a$  values of the amines in water and in the microemulsion are given in Table 2. These data can be fitted by correlation equations (1) and (2):

$$k_2 = -1.476 (\pm 0.46) + 0.19 (\pm 0.05)pK_a (\text{water}),$$

( $r$  0.888, for compound nos. 1–6, Table 2), (1)

$$k_2 = -1.893 (\pm 0.28) + 0.240 (\pm 0.031)pK_a (\text{microemulsion})$$

( $r$  0.961 for compound nos. 1–7, Table 2). (2)

Equation (1) with a low correlation coefficient describes water-soluble amines. Attempts to calculate with this equation the rate constants  $k_2$  of phenolysis of *p*-nitrophenyl acetate in the presence of hydrophobic amines lead to considerable overestimations (for example, for *N*-heptylpiperidine the calculated  $k_2$  is five times higher than that given in Table 2). Equation (2) involving  $pK_a$  values in microemulsions is well applicable to both hydrophilic and lipophilic amines. Apparently, in this case  $pK_a$  itself reflects the localization of the amine in the system and takes into account the effect of the amine microsurrounding on its electron-donor properties. It follows from Eq. (2) that the contribution of phenolysis to the reaction of the methyldi(*n*-octyl)amine–phenol ion pair with ace-

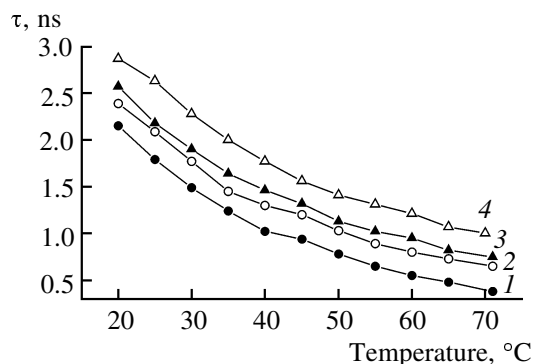
tate **I** in the microemulsion should be negligible, and this is the case.

The hydrolysis of esters **I** and **II** appears to be the only reaction pathway also in the system with methyldi(*n*-octyl)amine and 4-isononylphenol. Despite localization of both components of the pair in the hydrophobic region of the microemulsion, the basicity of the amine is insufficient to create a reactive nucleophilic center in 4-isononylphenol.

When discussing the possibilities of using microemulsions as reaction medium, one should take into account not only the effect of the microenvironment on the properties and behavior of reactants, but also the effect of reactants on the structure of the medium. This effect is particularly pronounced when the reactants are amphiphilic and are present in amounts comparable with those of the major components.

One of the methods used for studying supramolecular systems based on surfactants is the spin probe ESR method. The successful use of this method is due to the fact that amphiphilic spin probes are incorporated in the surface layer of microaggregates and the signal of the paramagnetic fragment reflects changes in its surrounding.

We showed previously that the ESR spectra of a spin probe, 4-(2-*n*-undecyl-3-oxyl-4,4-dimethoxyazolidinyl)butyric acid, in micellar solutions of cetyltrimethylammonium bromide contain broad external peaks [12]. Their presence indicates that the motion of hydrocarbon chains surrounding the nitroxyl moiety of the probe and determining its internal rotation is so slow that the hyperfine interaction of the unpaired electron with the magnetic moment of the nitrogen nucleus is not fully averaged [13]. Addition of 4-isononylphenol to the micellar solution led to an increase in the density of molecular packing in the interface



**Fig. 3.** Temperature dependences of the rotation correlation time  $\tau$  for a microemulsion based on cetyltrimethylammonium bromide ( $\varphi$  0.74) without 4-isononylphenol [pH: (1) 8.7 and (3) 13] and in its presence [pH: (2) 8.7 and (4) 13].

layer, due to formation of mixed micelles cetyltrimethylammonium bromide/4-isononylphenol.

In this study we obtained and analyzed the ESR spectra of spin probes introduced into a cetyltrimethylammonium bromide/water/*n*-butanol/*n*-hexane microemulsion ( $\varphi$  0.74) without modifying additives and in the presence of 4-isononylphenol at various pH values. The spectra of all the examined systems consist of three lines of the hyperfine structure, differing in the width and intensity. Such a pattern is characteristic of fast rotation of the paramagnetic moiety of the probe, when  $\tau\omega_A \gg 1$ , where  $\omega_A$  is the frequency of the anisotropy of the hyperfine interaction of the unpaired electron with the magnetic moment of the N nucleus, and  $\tau$  is the correlation time of rotation of the N–O group. The latter quantity is determined from the parameters of the ESR spectrum by the relationship [14]  $\tau = 6.65\Delta H_{+1}[(I_{+1}/I_{-1})^{1/2} - 1] \times 10^{-10}$  (s), where  $I_{+1}$  and  $I_{-1}$  are the intensities of the low- and high-field lines, respectively;  $\Delta H_{+1}$  is the width of the low-field component. The decrease of the temperature from 70 to 20°C does not affect the general spectral pattern, causing only the line broadening with a change in the line intensities.

Thus, the presence of butanol and hexane in the microdroplets considerably enhances the mobility of the hydrocarbon chains of the surfactant molecules. Apparently, this is due to the plasticizing effect of butanol and hexane. Also, butanol acting as a cosurfactant is inserted between cetyltrimethylammonium bromide molecules, “loosening” the interface layer and increasing the free volume for rotation of the hydrocarbon chains of these molecules. As a result of such a change in the internal structure of the aggregate in the microemulsion compared to micellar solution,

the correlation time  $\tau$  of rotation of the spin fragment, estimated from the ESR spectra, decreases. It should be noted that  $\tau$  depends on the pH of the microemulsion (Fig. 3, curves 1, 3). This may be due to the pH dependence of the molecular packing of the ionic surfactant and cosurfactant in the interface layer of the microemulsion (in contrast to micellar solutions). Apparently, as pH of a microemulsion is increased from 8.7 to 13.0, concentration of negatively charged hydroxide ions at the phase boundary alters the surface potential of the system, which results in redistribution of the components between the phases, in particular, in displacement of butanol from the phase boundary surface and in denser packing of surfactant molecules. Such an effect of pH was observed previously for a microemulsion based on sodium dodecyl sulfate, for which it was quantitatively shown that the content of bound butanol in a microdroplet decreased with an increase in the alkali concentration [15].

Introduction of 4-isononylphenol into a microemulsion decreases the mobility of the spin fragment of the probe (Fig. 3, curves 2, 4), because insertion of alkylphenol into the phase boundary surface increases the density of packing of hydrocarbon chains in the microdroplet. As a result, the rotation of the N–O group becomes more restricted, which is manifested in the ESR spectra and causes  $\tau$  to increase. The effect is pH-independent: The effects of the neutral (pH 8.7) and anionic (pH 13.0) forms of 4-isononylphenol on the mobility of the spin fragment are similar. This result appreciably differs from that observed in a micellar solution in which the anionic form of 4-isononylphenol causes stronger changes in the ESR spectrum than does the neutral form [12]. One of the possible causes of this difference is the higher surface potential of micellar aggregates in solutions of cetyltrimethylammonium bromide (130 mV [16]) compared to microemulsions (30 mV [6, 17]), which results in a smaller contribution of electrostatic interactions to solubilization of ionic reagent species and modifying additives.

To conclude, it should be noted that the reaction of carboxylic acid esters with phenols activated by alkalis and amines in microemulsions based on cationic surfactants depends on the value of the negative charge on the oxygen atom, which is determined by the properties of phenol and ionizing agent and by features of their localization in the system. The pathway of the ester cleavage can be controlled by using different bases for ionizing phenols. With hydrophobic phenols, the phenolysis pathway can be realized only in the presence of alkalis. With hydrophilic phenols, the phenolysis makes a significant contribution with both alkalis and highly basic hydrophilic

amines used as bases; in other cases, the base hydrolysis takes place.

### EXPERIMENTAL

We used commercial cetyltrimethylammonium bromide (Sigma) containing about 99.9% main substance. The solvents, phenols, amines, and *p*-nitrophenyl esters of carboxylic acids were purified by distillation or recrystallization, following standard procedures. The emulsion was prepared from 9.42 g of cetyltrimethylammonium bromide, 9.42 g of butanol, and 2.0 g of hexane; the volume fraction of water  $\varphi$  was 0.74.

The acid–base properties of the reagents used were studied by potentiometric titration or spectrophotometrically, by measuring the absorption of the ionized and nonionized species at different pH values (in borate and methylmorpholine buffers and in 0.01 M NaOH).

The reaction kinetics was studied spectrophotometrically (Specord UV–Vis) at 25°C in freshly prepared microemulsions. The reaction progress was monitored by variation of the optical density of solutions at  $\lambda$  400 nm (formation of *p*-nitrophenolate anion). The initial concentration of the substrate was  $5 \times 10^{-5}$  M, and the conversion, >90%.

The apparent pseudo-first-order rate constants  $k_{app}$  were determined from the dependence  $\log(D_{\infty} - D_t) = -0.434k_{app}t + \text{const}$ , where  $D_t$  and  $D_{\infty}$  are the optical densities of the solutions at time  $t$  and after the reaction completion, respectively. The  $k_{app}$  values were calculated by the least-squares method.

Formation of the ester interchange product in the microemulsion was confirmed in an experiment with equimolar amounts (0.01 M) of the *p*-nitrophenyl ester and sodium phenolate. The amount of the released acid was determined by potentiometric titration.

The ESR spectra were recorded on an RE-1306 radiospectrometer equipped with a temperature unit and interfaced with a computer. The ESR spectra were taken under conditions of slow passing through the resonance and in the absence of saturation. As spin probe we used 4-(2-*n*-undecyl-3-oxyl-4,4-dimethyl-oxazolidinyl)butyric acid. The procedure for introduction of spin probes into microemulsions is described in [18]. The ESR spectra were recorded in the range 20–70°C starting from higher temperatures at 4-isononylphenol concentrations of 0 and 0.04 M. The temperature was measured with an accuracy of  $\pm 0.5^\circ\text{C}$ .

### ACKNOWLEDGMENTS

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