Kinetics of the reactions of esters and primary amines in "oil—water" type microemulsions

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The possibilities of using "oil—water" type microemulsions as a medium for reactions of nucleophilic substitution in esters have been considered. The kinetics of the reactions of *p*-nitrophenyl acetate and caprylate with primary amines in the medium indicated has been studied. The hydrophoby factor, being of great importance for micellar solutions of surfactants, is not substantially manifested in detergent microemulsions: the rate constants of the reactions studied are in fact independent of the length of the alkyl radical of the nucleophile.

Key words: primary amines, esters, microemulsions, nucleophilic substitution, kinetics.

The high solubilizing ability of microemulsions (ME) and the highly developed surface of their interfaces make it possible to use these systems as microreactors for various chemical reactions.[1–6]

An isotropic, optically uniform "oil—water" ("oil" is a hydrocarbon) ME dispersion forms spontaneously when hydrocarbon, water, surfactant, and co-surfactant (usually a low-molecular alcohol) are mixed in certain proportions. The surface area of the interface can be varied in wide ranges by changing the ratios of the volumes of "oil" and water and the amount of the surfactant in the system. As a rule, in ME chemical processes occur inside or on the surface of a globule, and the large surface area of contact provides the convergence and interaction of water- and oil-soluble reagents.

ME make it possible to control the conditions of reactions and to separate solvents and reaction products by changing the temperature, which results in the lamination of ME.[7] Reactions in ME are often selective.[5] However, despite the sharp increase in interest in using ME as reaction media in the last decade, the kinetic aspects of processes occurring in ME are poorly studied. Among the few works devoted to reactions of nucleophilic substitution in ME based on nonionogenic and cationic surfactants, we should mention the detailed study of hydrolysis of esters of tetracoordinated phosphorus-containing acids in the presence of such nucleophiles as fluoride, hydroxyl, and iodobenzoate anions.[8,9]

In this work, we studied the possibilities of the application of ME as the medium for reactions of nucleophilic substitution in esters and the kinetics of these processes. Compounds with different lengths of hydrocarbon radicals were used to reveal the hydrophoby of reagents in ME.

Experimental

p-Nitrophenyl acetate (PNPA) and *p*-nitrophenyl caprylate (PNPC) were chosen as substrates; primary alkylamines containing from 2 to 18 hydrocarbon atoms in the radical were used as nucleophiles. The ME studied were optimized by composition according to the methods published previously[8,9]: the surfactant : co-surfactant molar ratio (in our case, cetylpyridinium bromide : *n*-butanol) was equal to 1 : 5, the fraction of hydrocarbon (hexane) was 10% of the total weight of the hydrophobic nucleus, and the ratio of aqueous (stretched) phase : nonaqueous phase was varied.

The high solubilizing ability of the ME studied made it possible to create concentrated water-containing solutions based on hydrophobic compounds. For example, in ME-1 of the composition (wt.%): cetylpyridinium bromide, 16.7; butanol, 16.1; hexane, 3.7; and water, 63.5, a solubility of *n*-cetylamine to a concentration of 0.2 *M* can be easily achieved, which is greater than its solubility in water by more than two orders of magnitude.

The solvents used, amines, and *para*-nitrophenyl esters were purified by standard methods. Samples of cetylpyridinium bromide were twice reprecipitated from an ethanolic solution with ether.

The kinetics of the reactions was studied spectrophotometrically on a Specord UV-VIS instrument at 25 °C. The run of the reaction was monitored by a change in the optical density of solutions at 400 nm (the formation of the *p*-nitrophenolate anion). The initial concentration of the substrate was $5 \cdot 10^{-5}$ mol L^{-1}, and the conversion was greater than 90%. The required values of pH in the systems were established by the addition of hydrochloric acid and were monitored on a pH-340 instrument.

The observed pseudo-first order rate constants (k_{obs}) were determined from the dependence $-\log(D_\tau - D) = -0.434\ k_{\text{obs}}\tau$ + const, where D and D_τ are the optical densities of solutions at the moment τ and at the end of the reaction, respectively. The k_{obs} values were determined by the least-squares method.

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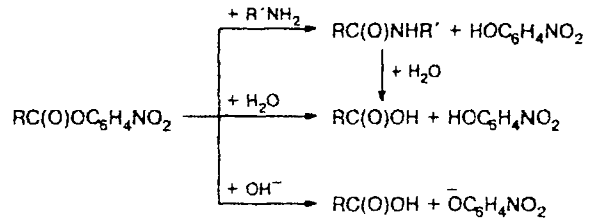
squares method. The second-order rate constants (k_2) were calculated in the linear region of the dependence of k_{obs} on the concentration of the amine (C_{am}) by the equation $k_2 = k_{obs} + k_0/C_{am}\alpha$, where k_0 is the rate constant of the alkali hydrolysis of the substrate determined at the specified pH in ME and α is the fraction of the neutral reactive form of the amine under conditions of the kinetic experiment. The α values were determined by the potentiometric titration of solutions of amines with a 0.1 *M* solution of HCl.

Results and Discussion

In aqueous solutions, the decomposition of esters in the presence of primary amines includes hydrolysis along with the main reaction of aminolysis.[10] In the simplified form, the scheme of the reaction can be presented as follows:

Scheme 1



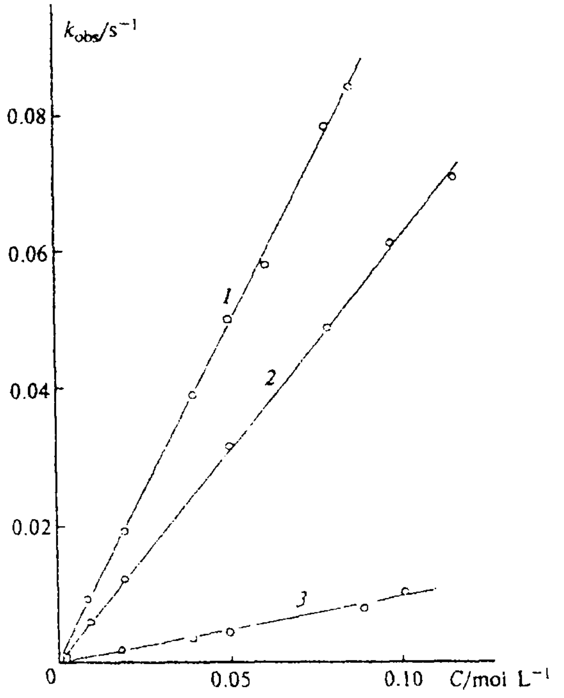


Fig. 1. Dependences of the observed rate constants (k_{obs}) of the reactions of PNPA with *n*-cetylamine (*1*), PNPA with *n*-decylamine (*2*), and PNPC with *n*-cetylamine (*3*) in ME-1 on the concentration of the nucleophile (pH 9.4, 25 °C).

The kinetic data characterizing the reactions of PNPA and PNPC with the amines in ME are presented in Tables 1—3 and Fig. 1. It follows from the results obtained that the observed rate constants of the sub-

Table 1. Rate constants of the reactions of *n*-cetylamine (C_{am} = 0.005 mol L^{-1}) with PNPA and PNPC in ME-1 at different pH values (25 °C)

pH	α	$k_{obs}\cdot10^2$ /s^{-1}		k_2 /mol^{-1} L s^{-1}		k_0* $\cdot10^3$ /s^{-1}	k_0* $\cdot10^4$ /s^{-1}
		PNPA	PNPC	PNPA	PNPC	PNPA	PNPC
8.15	0.05	0.64	0.048	2.48	0.174	0.17	0.40
8.50	0.11	1.05	0.095	1.88	0.161	0.20 0.19**	0.50
8.60	0.14	1.21		1.77		0.21	
8.90	0.24	1.93	0.200	1.61	0.166	0.25	0.85
9.40	0.50	5.0	0.450	2.00	0.172	0.57 0.52**	1.92
9.60	0.61	6.90	0.765	2.25	0.243	0.69	2.30
9.90	0.76	7.50		1.94		1.08	

* k_0 was determined in the borate buffer. ** In the buffer based on dimethylbenzylamine (this buffer was chosen to compare the contribution of the hydrolysis catalyzed by the general base mechanism with the contributions of the alkali hydrolysis and aminolysis to the cleavage of the esters studied).

Table 2. Rate constants of the reactions of *n*-alkylamines with PNPA and PNPC in ME-1 (pH 9.4, 25 °C)

Amine	α	C_n* /mol L^{-1}	k_{obs} /s^{-1}		k_2 /mol L s^{-1}	
			PNPA	PNPC	PNPA	PNPC
$C_6H_{13}NH_2$	0.38	0.019	0.032	0.0033	1.65	0.169
$C_8H_{17}NH_2$	0.40	0.020	0.041	0.0032	2.05	0.160
$C_{10}H_{21}NH_2$	0.40	0.020	0.039	0.0032	2.00	0.160
$C_{16}H_{33}NH_2$	0.50	0.025	0.050	0.0045	2.00	0.180
$C_{18}H_{37}NH_2$	0.50	0.025	0.053	0.0041	2.10	0.170
$C_2H_5NH_2$	—	0.02	0.036	0.0038	1.80	0.190
$C_2H_5NH_2$**	—	0.01	0.019	0.0017	1.94	0.170

* C_n is the concentration of the neutral form of the amine equal to $C_{am}\alpha$. ** At pH 10.

Table 3. Observed rate constants of the reactions of *n*-cetylamine (C_{am} = 0.05 mol L^{-1}) with PNPA and PNPC in ME of different compositions (pH 9.4, 25 °C)

Surfactant*	Composition of ME (wt.%)			k_{obs}/s^{-1}	
	BuOH	C_6H_{12}	H_2O	PNPA	PNPC
23.6	22.6	5.1	48.8	0.034	0.0031
16.7	16.1	3.7	63.5	0.050	0.0045
15.0	14.4	3.4	67.2	0.060	0.0058
11.8	11.3	2.6	74.3	0.086	0.0070
10.8	10.4	2.3	76.5	0.094	0.0081
9.5	9.1	2.0	79.4	0.098	0.0090

* Surfactant is cetylpyridinium bromide.

strates studied (k_{obs}) increase as the concentration of nucleophiles (Fig. 1) and the pH of the medium increase (see Table 1).

In ME, the dependences of k_{obs} of the reactions of PNPA and PNPC with the primary amines on the concentration of the nucleophile are linear (see Fig. 1). It is noteworthy that even for amines prone to micelle formation in aqueous solutions (for example, *n*-decylamine[11]) no deviation from this linearity is observed. The effective second-order rate constants of these processes, which were calculated taking into account the contribution of the alkali hydrolysis and the content of the reactive form of the amine averaged by volume, are presented in Table 1. The k_2 values obtained in ME-1 are ~5 times lower than k_2 for the corresponding reactions in aqueous solutions.[11] The possibility to create considerable concentrations of the nucleophile in ME can provide high effective rates, which is inaccessible in water in the case of low solubility of reagents.

It is shown, using the reactions of *n*-cetylamine with PNPA and PNPC as an example, that the second-order rate constant is unchanged within the pH range from 8 to 10. This suggests that the mechanism of the reactions remains unchanged under these conditions.

The rate constant of alkali hydrolysis of the substrates studied is independent of the nature of the buffers used and of the concentration of the buffer components. In addition, k_0 is considerably lower than k_{obs} for the reactions of PNPA and PNPC with the primary amines (see Table 1). This testifies that the aminolysis under the experimental conditions plays a determining role for the decomposition of the substrates studied.

Since detergent ME contain surfactants, they are similar in nature to micellar solutions. However, the properties of each system used as a reaction medium differ. For example, it is known that in aqueous micellar solutions the rates of reactions of esters with the primary amines depend substantially on the composition of mixed micellar aggregates and on the site of localization of the reagents, which is determined by their hydrophoby.[11] For the ME studied, the value of the hydrophoby factor is not substantial: the reaction rates of both PNPA and PNPC with the amines are independent of the length of the alkyl radical of the nucleophile; for example, the k_2 value is almost the same for ethylamine and *n*-octadecylamine (see Table 2).

In a wide range of concentrations for the whole series of amines considered, the same ratio of the observed constants of their reactions with PNPA and PNPC as for the alkali hydrolysis is retained: $k_{obs}(\text{PNPA})/k_{obs}(\text{PNPC}) \approx k_0(\text{PNPA})/k_0(\text{PNPC}) \approx 10$. In micellar solutions, this ratio changes strongly as the concentration of the reagents and their hydrophoby change.[11] This behavior can be associated with the fact that in ME the process occurs on the surface of a microglobule. Therefore, the localization of the nucleophile and substrate in one phase, which is so substantial in micellar systems, does not play a determining role in the case of ME.

The change in the ratio of components in ME results in the change in the reaction rates of nucleophilic substitution in the substrates studied. When the content of water in the system increases from 50 to 80 wt.%, the rate constants of the reactions of PNPA and PNPC with the primary amines increase by 2—3 times (see Table 3). This can be associated with the increase in the surface of the interface due to the increase in the volume of the aqueous phase[8] and with the increase in the polarity of ME, which is a favorable factor for S_N2 processes.

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