Kinetics of reactions of ethyl *p*-nitrophenyl ethylphosphonate with anionic nucleophiles in a detergentless microemulsion

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The kinetics of reactions of ethyl *p*-nitrophenyl ethylphosphonate with anionic nucleophiles in a detergentless water—oil microemulsion, formed in the *n*-hexane—water—isopropyl alcohol system, was studied. The rate constants of the reactions in the microemulsion are higher than those in aqueous solutions and increase with increasing isopropyl alcohol : water ratio.

Key words: phosphorylation, anionic nucleophiles, kinetics, detergentless microemulsions.

Microemulsions (ME) are transparent stable dispersions of microdrops (radius of 0.5-5 nm) of a hydrocarbon in water or water in a hydrocarbon, whose formation and stability are promoted by additives of surfactants that decrease the interfacial surface tension.^{1,2} The possibilities of performing reactions in liquid media are extended due to the capability of ME to solubilize different compounds. The specific features of solubilization and interphase distribution of reagents in ME can result in the acceleration of some and inhibition of other reactions.³⁻⁷

"Detergentless" ME containing no typical surfactants are formed in triple systems containing a hydrocarbon, water, and some alcohols that possess surface activity and are capable of stabilizing microdrops. Detergentless ME of the water/oil (W/O) type have been proposed as a medium for enzyme-catalyzed processes.⁸⁻¹⁰ In such ME, some reactions of nucleophilic substitution occur much more rapidly than in aqueous media. For example, in the system consisting of 2-butoxyethanol (60 mol.%), n-decane (20 mol.%), and water (20 mol.%), the rate constant of alkaline hydrolysis of 2,4-dinitrochlorobenzene is 10³ times higher than that in water.⁵ It has been found that oxidative processes with the participation of hypochlorite and involving the stage of nucleophilic substitution occur rapidly in detergentless ME based on the isopropyl alcohol-n-hexane-water system.⁶ In this work, we studied the kinetics of phosphorylation of anionic nucleophiles for the last system. Ethyl p-nitrophenyl ethylphosphonate was used as the substrate because the kinetics of its reactions with anionic nucleophiles X⁻

 $(EtO)EtP(O)OC_6H_4NO_2-p + X^-$ $(EtO)EtP(O)X + ^-OC_6H_4NO_2-p$

in an aqueous medium has been previously studied.^{11,12}

Experimental

Phenols, acetaldoxime, *n*-hexane, and isopropyl alcohol were distilled prior to use. Ethyl *p*-nitrophenyl ethylphosphonate was prepared by the known method.¹³ Solutions of NH₄F (pure grade) and NaOH (reagent grade) and ME samples were prepared with bidistilled water. The kinetics of the reactions was studied in ME containing (wt.%) n-C₆H₁₄ (11.9), PrⁱOH (58.5), and H₂O (29.6) (ME-1) and n-C₆H₁₄ (41.3), PrⁱOH (48.7), and H₂O (10.0) (ME-2). The composition of ME was identical to that used previously.⁶ ME was obtained by mixing of the components.

The kinetics of the reactions was studied by spectrophotometry on an SF-26 instrument. The optical density (D) at 400 nm of the systems containing the substrate increases during the reaction due to the formation of *p*-nitrophenolate. The reactions were carried out in thermostatted (± 0.5 °C) quartz cells. The initial concentrations of the substrate did not exceed 10^{-4} mol L⁻¹. The observed first-order rate constants k_1 were determined by the equation

$$\ln(D_{\rm L} - D) = -k_1 t + \ln(D_{\rm L} - D_0),$$

where D_0 , D, and D_L are the optical densities of the system at the beginning, at the moment r, and at the end of the reaction, respectively. The k_1 values were calculated by the weighted least-squares method. The effective second-order rate constants k_2 were calculated by the formula $k_1/C_0 = k_2$, where C_0 is the concentration of the corresponding anion in the total volume of the system.

Results and Discussion

ME-1 and ME-2 are microemulsions of the W/O type.⁶ The surface of aqueous microdrops is stabilized by isopropyl alcohol, the whose hydroxyl group is solvated by water, and the alkyl radical is present in *n*-hexane surrounding the microdrops. Biphilic solvation

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of isopropyl alcohol provides the stability of the ME due to a decrease in the free surface energy.²

The reaction rates of the S substrate with the hydrophilic anions HO⁻ and F⁻ in the ME-1 and ME-2 systems and in water under the experimental conditions (at $C_0 >> [S]$) follow the kinetics of the pseudo-first order

$$-d[S]/dt = k_2 C_0[S], (1)$$

where $k_2C_0 = k_1$ is the observed first-order rate constant and k_2 is the effective second-order rate constant containing the contribution from the reactions in the volume of microdrops and interphase surface layer. The invariability of k_2 with variation of C_0 indicates the first order with respect to the nucleophile (Table 1). A similar kinetic behavior has been observed previously^{14.15} for the reactions of phosphoric esters with the HO⁻ and F⁻ anions in detergent ME of the W/O type containing a cationic or non-ionogenic surfactant.

For the reactions of *p*-nitrophenyl phosphates with organic anions (phenolates, oxime anions) containing hydrophobic radicals, Eq. (1) is also fulfilled in aqueous solutions.^{11,16,17} The only exception is the reaction of the substrate with *p*-octyl phenolate, for which the dependences of the rate constants k_1 in aqueous solutions on the nucleophile concentration are complicated due to the formation of *p*-octyl phenolate of anionic micelles.¹² For the reactions of the substrate with phenolates and the acetaldoxime anion in the ME-1 and ME-2 systems when C_0 is varied, k_2 decreases substantially as the concentration of nucleophiles increases (Table 2).

The observed differences in the kinetics of the reactions involving hydrophilic inorganic anions (HO⁻ and F^-) and organic anions with some hydrophobicity can be a consequence of different localizations of these two groups of anions in the ME under study. As is known,^{1,2} the W/O type ME contain a high-polarity region inside water microdrops, a low-polarity region in the hydrocar-

Table 1. Rate constants of the reactions of ethyl *p*-nitrophenyl ethylphosphonate with HO⁻ and F⁻ anions in aqueous solutions and microemulsions of the W/O type at 25 °C

Anion	Medium	C ₀ /mol L ⁻¹	$\frac{k_1 \cdot 10^2}{/s^{-1}}$	k_2 /L mol ⁻¹ s ⁻¹
H0-	H ₂ O	0.13 0.30	1.99 4.18	0.153 0.139
	ME-1	0.05 0.10	1.18 2.43	0.236 0.243
	ME-2	0.0024 0.0048	0.120 0.229	0.500 0.474
F-	H ₂ O	1.0 1.8	0.692 1.31	0.0069 0.0073
	ME-1	0.05 0.10	0.0548 0.112	0.0110 0.0112
	ME-2	0.00757 0.0103	0.0251 0.0323	0.033 0.032

bon phase, and an interphase surface layer that possesses an intermediate polarity. The substrate containing polar (PO and NO₂) and hydrophobic (Et, Ph) groups is amphiphilic and, hence, mainly located on the interphase surface, although an insignificant fraction can be present in the microdrops and hexane. The microdrops contain

Table 2. Rate constants of the reactions of ethyl *p*-nitrophenyl ethylphosphonate with anions of sodium phenolates and the acetaldoxime anion in aqueous solutions and W/O microemulsions at 25 °C

Anion	Medium	C_0 /mol L ⁻¹	$\frac{k_1 \cdot 10^3}{/\mathrm{s}^{-1}}$	k ₂ /L mol ⁻¹ s ⁻¹
MeCHNO-	H ₂ O	0.0166 0.0327 0.0415	1.65 3.82 3.77	0.099 0.117 0.091
		0.0654 0.0830	6.90 7.87	0.106 0.095
	ME-1	0.0128 0.0256 0.0330 0.0515 0.0655 0.0768	2.79 4.68 5.05 6.74 7.84 8.89	0.218 0.183 0.153 0.131 0.120 0.116 0.110
		0.098	13.0	0.099
	ME-2	0.0042 0.0083 0.0166 0.0308 0.0415 0.0750 0.0830	1.22 1.84 3.33 3.57 3.69 3.94 3.97	0.290 0.222 0.201 0.116 0.089 0.053 0.048
PhO	ME-1	0.010 0.020 0.050 0.100 0.200 0.300	0.625 1.16 1.31 1.49 1.85 2.16	0.0625 0.0580 0.0262* 0.0149 0.0093 0.0072
	ME-2	0.010 0.020 0.030 0.040 0.150 0.225 0.300	0.606 1.07 1.45 1.56 4.22 5.56 7.30	0.0606 0.0535 0.0483 0.0390* 0.0281 0.0247 0.0243
<i>n</i> -C ₈ H ₁₇ C ₆ H ₄ O [−]	ME-1	0.010 0.020 0.050 0.100 0.200 0.300	0.581 0.92 1.56 1.68 1.97 2.11	0.0581 0.0460 0.0312 0.0168 0.0098 0.0070
	ME-2	0.032 0.063 0.079 0.095 0.158 0.237 0.316	1.76 2.13 2.38 2.96 3.71 5.06 6.80	0.0550 0.0338 0.0301 0.0312 0.0235 0.0214 0.0215

* In water at the same concentration of phenolate, $k_2 = 0.016 \text{ L mol}^{-1} \text{ s}^{-1} \text{ at } 25 \text{ °C}.^{12}$ some amount of isopropyl alcohol; therefore, their polarity is lower than that of pure water, and the solubility of the ionic compounds NaOH and NH₄F (located in the microdrops) decreases in the ME-1 and ME-2 systems. The maximum decrease in the solubility of NaOH and NH₄F was observed in ME-2 with a higher PrⁱOH : H₂O ratio. Due to a low solubility of the ionic compounds, the rate constants of the substrate with the HO⁻ and F⁻ anions in the ME-1 and ME-2 systems were determined in a narrow C_0 interval (see Table 1).

By contrast, the solubility of sodium phenolates and MeCHNONa in the ME-1 and ME-2 samples is higher than that in water. Probably, ions of salts of organic acids are located in the interphase surface layer. A lower polarity of this region favors the association of ions to form ionic pairs. The observed decrease in k_2 with an increase in the concentration of organic anions in ME-1 and ME-2 (see Table 2) is related to the formation of ion pairs and their low reactivity as compared to that of free ions.

The equation for the dissociation constant of the ion pairs has the form

$$K = C_0 a^2 / (1 - a),$$

where a is the degree of dissociation of the ion pairs. Using the equation¹⁸

$$k_2 = k_{\rm p} + (k_{\rm i} - k_{\rm p})a_{\rm s}$$

we can find the rate constants of the reactions involving the ion pairs (k_p) and free ions (k_i) . The estimation

Table 3. Estimation of the dissociation constants of ion pairs (K) and rate constants of the reactions of substrates with organic anions involving ion pairs (k_p) and free ions (k_i)

Anion	ME	K	k _p	k;	
		$/mol L^{-1}$	L mol ⁻¹ s ⁻		
MeCHNO ⁻	ME-1	0.0029	0.026	0.54	
	ME-2	0.017	0	0.28	
PhO ⁻	ME-1	0.011	0	0.090	
	ME-2	0.011	0.009	0.092	
<i>n</i> -C ₆ H ₁₇ C ₆ H ₄ O	ME-1	0.017	0	0.084	
	ME-2	0.017	0.006	0.073	

(performed on the basis of this equation by the leastsquares method) of the constants K, k_i , and k_p for the reactions of the substrate with organic ions (by the data in Table 2) showed (Table 3) that $k_i >> k_p$ in all cases. The low reactivity of the ion pairs involving organic anions is probably related to the formation of solventseparated ion pairs.¹⁸

The influence of ME on the reaction rates is characterized by the rate constants k_2 , which increase by 1.6– 1.7 times for the reactions with the HO⁻ and F⁻ ions on going from an aqueous medium to the ME-1 system (see Table 1). In the ME-2 system, the reaction rates increase more sharply: for HO⁻, by 3.3 times, and for F⁻, by 4.6 times (see Table 1). A different character of the influence on the phosphorylation of anionic nucleophiles was observed for O/W detergent ME. It has been found¹⁵ that ME of the O/W type containing a cationic (cetyl trimethylammonium bromide) or non-ionogenic (polyoxyethylene-(10) oleate ester) surfactant inhibit the phosphorylation of the HO⁻ and F⁻ anions by *p*-nitrophenyl phosphates.

The phosphorylation of the organic anions (phenolate and oximate ions) in the ME-1 and ME-2 systems is also faster (see Table 2) than that in aqueous solutions; however, one should take into account a change in the state of these nucleophiles in a microemulsion medium due to the association of their ions in ion pairs.

The characteristic feature of ME is the possibility of phase inversion with temperature increase, which results² in a change in the type of ME on going from W/O to O/W. The phase inversion can result in a change in the distribution of the reagents in ME and their reactivity. In this connection, we studied the temperature dependences of the reaction rate constants (Tables 4 and 5). In the ME-1 and ME-2 systems, these dependences are described by the Arrhenius equation with rather high correlation coefficients (r > 0.95), which indicates the absence of phase inversion in the ME-1 and ME-2 systems in the temperature interval under study.

For the reactions with a more reactive HO⁻ ion, the observed activation energy E_a and the pre-exponent A are lower than those in the case of the reaction with the F⁻ ion (see Table 4). An increase in the k_2 rate constants for the reactions with the HO⁻ and F⁻ ions in the ME-1 and ME-2 systems, as compared to those in an

Table 4. Rate constants and parameters of the Arrhenius equation for the reactions of ethyl p-nitrophenyl ethylphosphonate with HO⁻ and F⁻ anions in aqueous solutions and W/O microemulsions

Anion	Medium	C_0 /mol L ⁻¹	$k_2 \cdot 10^2 / L \text{ mol}^{-1} \text{ s}^{-1}$				E _a	logA	
			15 °C	25 °C	35 °C	45 °C	55 °C	/kJ mol ⁻¹	
но-	H ₂ O ME-1 ME-2	0.30 0.02 0.0048	0.082	0.139 0.234 0.477	0.236 0.375 0.921	0.407 0.590 1.29	1.04 2.02	40.6±1.1 40.0±2.2 38.1±3.1	4.27±0.18 4.37±0.36 4.37±0.52
F-	H ₂ O MĚ-1 ME-2	0.50 0.10 0.01	-	0.0064 0.011 0.0323	0.0134 0.024 0.0659	0.0284 0.043 0.130	0.0470 0.082 0.225	54.9±2.4 53.8±1.6 53.0±1.2	5.43±0.41 5.48±0.27 5.79±0.20

Anion	Medium	C ₀ /mol L ⁻¹	k ₁ · 10 ² /s ⁻¹			Ea	logA	
			25 °C	35 °C	45 °C	55 °C	/kJ mol ^{−1}	
MeCHNO ⁻	H ₂ O	0.05	0.515	0.990	1.44	1.94	35.6±4.0	3.98±0.67
	ME-1	0.05	0.645	1.33	1.97	3.42	44.0±3.1	5.53±0.52
	ME-2	0.075	0.394	0.656	1.09	2.16	45.5±3.3	5.55±0.55
PhO ⁻	H2O	0.05	0.079	0.174	0.362	0.547	53.3±4.1*	6.27±0.68*
	ME-1	0.20	0.185	0.425	0.591	1.130	46.9±4.9	5.52±0.82
	ME-2	0.20	0.437	0.805	1.63	2.28	46.2±3.7	5.74±0.63
<i>n</i> -C ₈ H ₁₇ C ₆ H ₄ O ⁻	H ₂ O	0.05	0.138	0.210	0.444	0.944	52.8±5.7*	6.34±0.95*
	ME-1	0.20	0.197	0.369	0.676	1.18	48.6±0.2	5.81±0.03
	ME-2	0.20	0.475	0.845	1.73	2.07	41.9±5.8	5.04±0.97

Table 5. Rate const. at and parameters of the Arrhenius equation for reactions of ethyl p-nitrophenyl ethylphosphonate with anions of phe-jolates and the acetaldoxime anion in aqueous solutions and W/O microemulsions

* According to Re: 11

aqueous medium, is mainly determined by a decrease in E_{a} . For the HO⁻ and F⁻ ar ons (see Table 4) in water, ME-1, and ME-2, $logk_2$ ar $\Rightarrow E_a$ are interrelated, which is reflected (at 25 °C) by the regression equation

$$\log k_2 = -0.092E_a + 1.0$$
 (= 6, r = 0.964, sd = 0.22).

It follows from this equator that the phosphorylation of the HO⁺ and F⁺ anions in water and ME of the W/O type compose a reaction ser as with the general mechanism of the medium effect on the reactivity of nucleophiles.¹⁹ The observed E_a value and the reactivity of the hydrophilic anions in the ME under study is determined by the distribution of the an ons between the volume of microdrops and the interphase surface layer, the solvation of the anions by the components of the medium, and the polarity of the microenvironment that depends on the concentration of isopropyl alcohol in the systems.

For the reactions with organic anions, the E_a values were determined in the region of C_0 , where ions are predominantly associated ir ion pairs, which is indicated by a substantial decrease in the k_2 constants obtained for low values of ((see Table 2)). Therefore, for the reactions with phen lates and oximate, the E_a values in the ME-1 and ME-2 systems are determined by ion association along v th the above mentioned factors. As a result, the E_a value in the ME-1 and ME-2 systems is lower for the reactions with phenolates (see Table 5) and somewhat ni her for the acetaldoxime anion than those in aquecus olutions.

Thus, this work showed the in the studied ME of the W/O type the phosphoryla io - of anionic nucleophiles is faster than that in aqueo-s tions, a lower (relative to we or) solubility of inorganic salts and a higher solubility coorganic salts in such ME should be taken into account.

lutions. For these reac-

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