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Supramolecular Systems Based on Aminomethylated Calix[4]resorcinarene and a Cationic Surfactant: Catalysts of the Hydrolysis of Esters of Phosphorus Acids

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Abstract—Kinetics of alkaline hydrolysis of 4-nitrophenyl esters of tetracoordinated phosphorus acids in micellar solutions of aminomethylated calix[4]resorcinarene containing sulfonatoethylene groups on the lower rim of the macrocycle, 4-aza-1-hexadecyl-azoniabicyclo[2.2.2]octane bromide and their mixtures was investigated spectrophotometrically. It is established that the catalytic effect of aggregates depends on the concentration of calixarene and surfactants, pH, presence of lanthanum salt and reaches more than two orders of magnitude. The parameters of the catalyzed reactions and their dependence on the composition are determined.

Keywords: calix[4]resorcinarene, alkylated 1,4-diazabicyclo[2.2.2]octane, hydrolysis, catalysis, esters of phosphorus acids.

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INTRODUCTION

In recent years, considerable attention has been given to the development of new catalytic systems based on the principles of supramolecular chemistry. A key role is assigned to designing catalytic compositions based on calixarenes, which have high selectivity for many organic reactions, particularly the hydrolysis of esters of phosphorus acids [1–4]. This reaction is a convenient model for studying the patterns of the most important biochemical reactions. Moreover, the cleavage of phosphoester bonds is one way of detoxification for organophosphorus neurotoxins and toxicants [5, 6]. A wide range of studies of this process with traditional surfactants (anionic, cationic, nonionic) acting as catalysts have already been published [2, 7, 8].

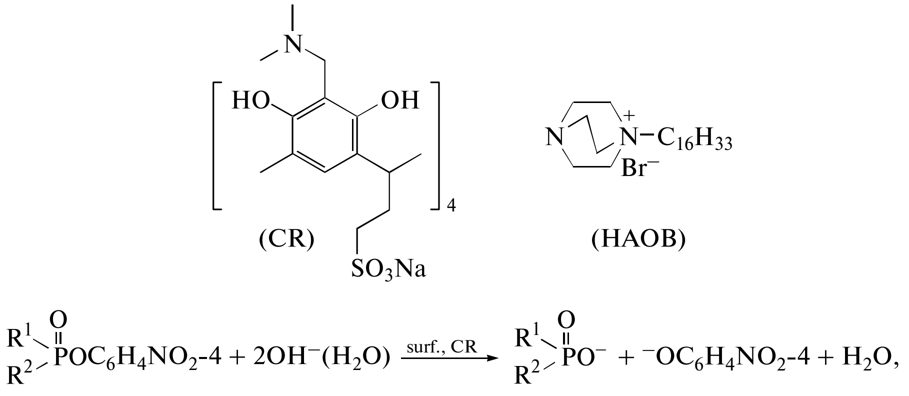
The advantage of applying macrocyclic receptors is that the cavity size and conformation of the molecule can be varied by its directed functionalization [1, 9]. The presence of additional binding sites in the molecules of calixarene and the possibility of implementing inclusive interactions that enhance the effect of the concentration of reagents and are conducive to the catalytic effect of systems suggest the promising application of calixarenes in catalytic systems. It should be noted that calixarene–surfactant systems are relatively new and have a multitude of features, as compared to conventional catalysts. The study of self-organizing mixed compositions based on calixarenes and surfactants is thus undoubtedly of interest and could be useful in the development of catalysis.

In this work, the influence of supramolecular systems based on the new calix[4]resorcinarene, which contains aminomethylated fragments on the upper rim and sulfonate groups on the lower rim of the macrocycle (CR) and a cationic surfactant 4-aza-1-hexadecyl-azoniabicyclo[2.2.2]octane bromide (HAOB), on the reaction of hydrolytic decomposition of 4-nitrophenyl esters of tetracoordinated phosphorus acids—4-nitrophenyl-O-butylchloromethylphosphonate (NBCP) and bis(4-nitrophenyl)methylphosphonate (BNMP) (Scheme 1)—was investigated.

Table 1. ^{31}P NMR chemical shifts of the reaction products of hydrolysis NECP and NBCP in the absence and presence of HAOB and CR at 25°C

System	δ^{31}P, ppm	System	δ^{31}P, ppm
NECP	14.4	NBCP–CR	13.9
NECP–HAOB	14.0	NECP	(17.7)
NECP–CR	14.2	NBCP	(18.5)

Note: C_{NECP} = 0.02 mol/l, C_{NBCP} = 0.02 mol/l, C_{HAOB} = 0.05 mol/l, C_{CR} = 0.01 mol/l (the chemical shift of NECP and NBCP in water, respectively).



(CR) (HAOB)

$$\mathrm{R^1R^2P(O)OC_6H_4NO_2\text{-}4} + 2\mathrm{OH^-(H_2O)} \xrightarrow{\text{surf., CR}} \mathrm{R^1R^2P(O)O^-} + {}^-\mathrm{OC_6H_4NO_2\text{-}4} + \mathrm{H_2O},$$

$R^1 = ClCH_2$, $R^2 = OC_4H_9$ (NBCP); $R^1 = CH_3$, $R^2 = OC_6H_4NO_2$-4 (BNMP).

$R^1 = ClCH_2$, $R^2 = OC_2H_5$ (NECP).

Scheme 1.

The alkaline hydrolysis of 4-nitrophenyl-O-ethylchloromethylphosphonate (NECP) was also examined as evidence for the mechanism of the process.

EXPERIMENTAL

Our CR macrocycle was prepared by reacting calix[4]resorcinarene with the sulfonatoethylene fragment on the lower rim with bis(dimethylamino)methane. The CR structure was confirmed by ^{1}H NMR spectroscopy and elemental analysis. HAOB was prepared by reacting 1,4-diazabicyclo[2.2.2]octane with cetylbromide according to the procedure in [10]. The NBCP, BNMP, and NECP substrates were synthesized as in [11, 12].

^{31}P NMR spectra of NBCP, NECP, and their hydrolysis products were recorded on a Bruker MSL-400 instrument (162 MHz) relative to an external standard (H_3PO_4).

The reaction kinetics was studied spectrophotometrically by an increase in optical density of the absorption band of 4-nitrophenol anion at 400 nm on a Specord UV-Vis spectrophotometer in thermostatted cuvettes. The rate constants observed were determined from an equation of the first order. The substrate (NBCP, BNMP) concentration at the beginning of the reaction was 5×10^{-5}–1×10^{-4} mol/l. The concentration of free bromide ion was determined by an I-160MI ion meter with an ELIS-131Br bromine-selective electrode. A 10101 ESr-electrode was used as a reference electrode.

Table 2. Degree of binding of a bromide ion with HAOB–CR (0.001 M) aggregates in water, 25°C

c_{HAOB}, mol/l	β	c_{HAOB}, mol/l	β
0.01	0.79	0.06	0.77
0.02	0.74	0.08	0.77

RESULTS AND DISCUSSION

The hydrolysis of esters of phosphorus acids was selected as a model of the process. The test process begins with the release of 4-nitrophenol anion fixed by the spectrophotometric method for the absorption band at 400 nm and the corresponding acid, whose formation was confirmed by ^{31}P NMR spectroscopy (Table 1). As in the absence and presence of CR and surfactant, the formed acids are characterized by signals in the 13.9–14.4 ppm range. Initial phosphonates (NECP and NBCP) are characterized by signals of 7.17 ppm and 18.5 ppm, respectively (Table 1).

It should be noted that the amphiphilic additives (surfactant and calixarene) used in our study of hydrolysis are able to self-organize. The presence of associates in both individual and mixed aqueous solutions of surfactant and calixarene was shown earlier by tensiometry, conductivity, potentiometry and dynamic light scattering. It was established that aggregates form in aqueous solutions of HAOB at concentrations above 0.001 mol/l corresponding to the critical micelle concentration (CMC_1), and the structure is altered at a concentration of 0.011 mol/l (CMC_2) [13]. In CR solution, the formation of aggregates occurs at $CMC_1 = 9.3 \times 10^{-3}$ mol/l [14]. The formation of mixed associates in a binary HAOB–CR system ($c_{CR} = 0.001$ mol/l) and alteration of the structure occurs in the concentration of 3–10 times lower than in the individual solutions of surfactant and the macrocycle [14]. In addition, a lower degree of counterion binding (β) equal to 0.74–0.79 (Table 2) is characteristic of mixed systems, whereas, according to [14] β value is equal to 0.81–0.89 for individual surfactant solutions. The degree of binding for counterions determines the surface potential of micelles and hence the effect of the concentration of reactants and catalyst efficiency.

The change in the colloidal state of individual and mixed systems based on HAOB and CR is manifested in the kinetics of hydrolysis of esters of phosphorus

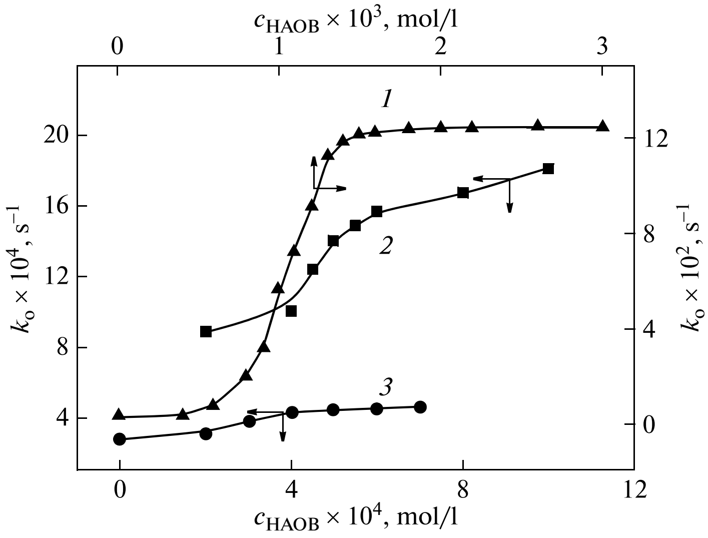


Fig. 1. Dependences of the k_o hydrolysis reaction of NBCP on the concentration of GAOB in the absence (*1*) and presence of CR (*2*, *3*), $c_{CR} = 0.001$ mol/l, $c_{NaOH} = 0.001$ mol/l (*1*, *2*), pH 11 (*1*), pH 10 (*2*), pH 9 (*3*), 25°C.

acids. The observed rise in the rate constants (k_o, s^{-1}) of the hydrolysis of NBCP with a subsequent tendency to leave the dependence at a plateau occurs upon an increase in surfactant concentration (Fig. 1). Such a dependence is typical for micellar-catalyzed reactions, and according to the pseudo-phase model of micellar catalysis is explained by the concentration of the reactants in a colloidal phase, i.e., the transitioning of reagents (hydroxide ions and the phosphoric substrate) from the bulk of the solution into aggregates and the complete binding of the phosphonate by aggregates in the area of high concentrations of surfactant [15, 16]. Table 3 shows the parameters of the catalyzed reaction, calculated using the equation [15]

$$k_н = \frac{k_m K_S(c_{surf} - CMC) + k_0}{1 + K_S(c_{surf} - CMC)}, \qquad (1)$$

where k_o is observed rate constant of first order, s^{-1}; k_0 and k_m are reaction rate constant in bulk solvent and micellar phase, s^{-1}; K_S is binding constant of the substrate with the aggregates, l/mol; c_{surf} is concentration of surfactant, mol/l.

In the individual HAOB solutions at pH 11, the studied process is characterized by a relatively high binding constant of the substrate with the aggregates (more than three orders of magnitude) and the magnitude of the catalytic effect of the system (k_m/k_0), 46. The presence of calixarene in HAOB solution leads to a reduction in CMC$_1$, an increase in K_S, and to a lower pH via the acid–base interactions of amino groups with water. As can be seen from Table 3, the catalytic effect of binary HAOB–CR systems is lower than the individual solutions of cationic surfactant, but the heightened catalytic effect of mixed aggregates is observed at lower pH.

We studied the effect of the associates formed by individual CR molecules on the hydrolytic cleavage of esters of phosphorus acids using the example of the alkaline hydrolysis of BNMP. Raising the CR concentration increases the observed rate constants (Fig. 2). At the same time, the dependence (as in the individual HAOB solutions) tends to a plateau at high concentrations, indicating the complete binding of the substrate (phosphonate) by macrocycle aggregates. Table 4 lists the parameters of catalyzed hydrolysis of BNMP calculated according to Eq. (1). It can be seen that at pH 9.0, the system under investigation is characterized by a low CMC value (as stated above, at the neutral pH the CMC of macrocycle is 9.3×10^{-3} mol/l) and a catalytic effect of 5.

Table 3. Parameters of NECP hydrolysis catalyzed by HAOB and HAOB–CR aggregates at 25°C

System	pH	k_m, s^{-1}	K_S, l/mol	CMC$_1 \times 10^3$, mol/l	k_m/k_0^c
HAOB^a	11	0.16	4900	0.89	46
HAOB–CR^{a,b}	10	0.0019	14000	0.35	5.0^c
HAOB–CR^b	9.0	0.00051	6900	0.18	14^c

Note: ^{a} $C_{NaOH} = 0.001$ mol/l; ^{b} $C_{CR} = 0.001$ mol/l; ^{c} The effect of aggregates is relative to the k_o alkaline hydrolysis of NECP in the absence of CR and HAOB.

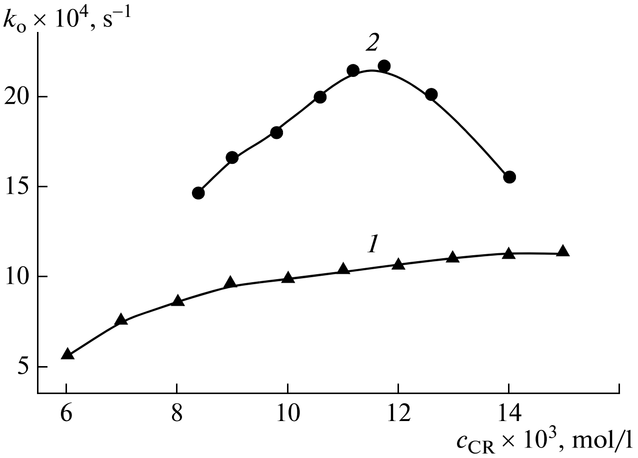


Fig. 2. Dependences of the observed rate constant for BNMP hydrolysis on CR concentration in the absence (*1*) and presence (*2*) of $La(NO_3)_2$. (*2*) $c_{La(NO_3)_2} = 0.0056$ mol/l. (*1*) pH 9.0; (*2*) pH 7.1; 25°C.

It was of interest to assess the role of new agents, salts of La(III), that exert a catalytic effect on the hydrolysis of esters of phosphorus acids by electrophilic mechanism [17] and thereby increase the resultant action of system on the process. It was established that the presence of $La(NO_3)_2$ leads to a reduction in pH from 9.0 to 7.1 (as a result of the hydrolysis of lanthanum salts [18]) and an increase in the catalytic effect of up to 650 (i.e., by a factor of 130) (Table 4). In addition to the contribution of homogeneous (electrophilic) catalyst, this phenomenon could be due to an increase in substrate binding by CR aggregates (the binding constant K_S of the substrate by CR aggregates in the presence of salts increases fourfold, Table 4), and to an increase in the proportion of the cationic form of the CR with protonation of nitrogen atoms of calixarene in a more acidic environment [19]. An increase in the proportion of cationic centers favors the binding of the nucleophilic reagent (hydroxide ion).

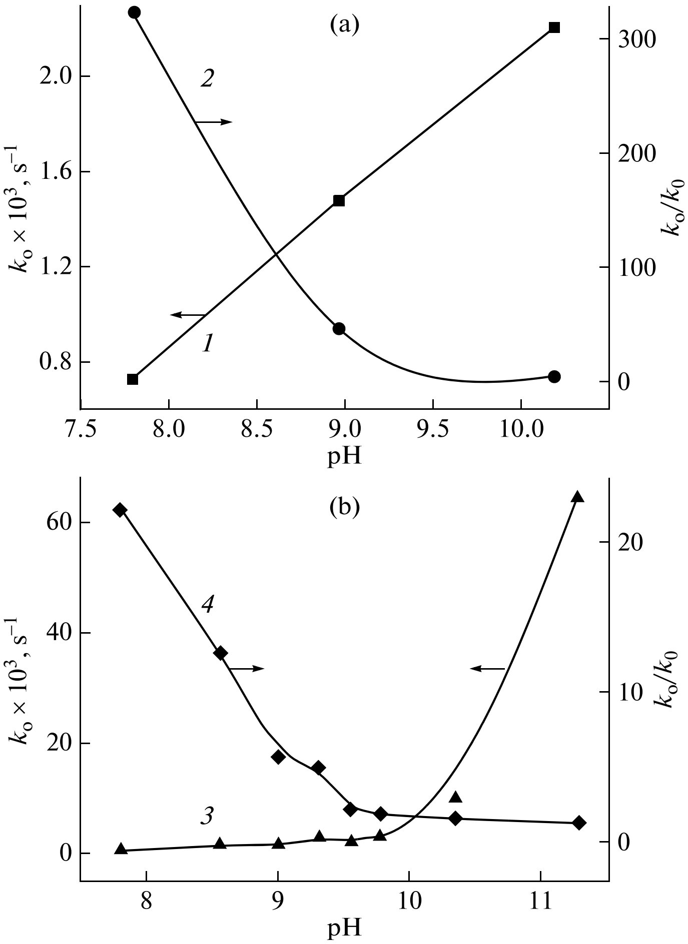


Fig. 3. Dependences of the observed reaction rate constant of alkaline hydrolysis of NBCP (*1*, *2*) and BNMP (*3*, *4*) in the presence of 0.014 mol/l CR (*1*, *3*) and the catalytic effect of CR (*2*, *4*) on pH at 25°C.

Table 4. Parameters of BNMP hydrolysis catalyzed by CR aggregates at 25°C

System	pH	$k_m \times 10^3$, s^{-1}	K_S, l/mol	KKM$_1 \times 10^3$, mol/l	$k_0 \times 10^5$,^{b} s^{-1}	k_m/k_0^d
CR	9.0	1.3	440	5.2	26	5.0
CR–La(NO$_3$)$_2^a$	7.1	2.2	1800	7.5	0.34 (20^c)	650 (11^e)

Notes: ^{a} $C_{La(NO_3)_2} = 0.0056$ mol/l.

^{b} k_0 alkaline hydrolysis of BNMP in the absence of CR [12].

^{c} k_0 alkaline hydrolysis of BNMP in La(NO$_3$)$_2$ solution in the absence of CR.

^{d} The effect of aggregates is relative to the k_0 alkaline hydrolysis of BNMP in the absence of CR and CR–La(NO$_3$)$_2$ mixes, respectively.

^{e} The effect of aggregates is relative to the k_0 alkaline hydrolysis of BNMP in La(NO$_3$)$_2$ solution.

The different distribution of charge on a molecule of calix[4]resorcinarene upon a change in the pH of the medium thus demonstrates that the action of CR on the reaction kinetics of alkaline hydrolysis is pH-dependent. This is also evidenced by a reduction of the catalytic effect of the CR in the reaction of alkaline hydrolysis of the investigated substrates with increasing pH. Raising pH from 7.8 to 10.2 (in the case NBCP) and up to 11.3 (in the case BNMP) leads to a reduction of the catalytic effect of the macrocycle, respectively, from 320 to 4 (i.e., eightyfold) (Fig. 3a) and from 22 to 1.3 (i.e., by a factor of 17) (Fig. 3b).

CONCLUSIONS

Our investigations have shown that a system based on aminomethylated calix[4]resorcinarene containing sulfonatoethylene groups on the lower rim of the macrocycle, cationic surfactant 4-aza-1-hexadecyl-azoniabicyclo[2.2.2]octane bromide and their mixtures have a catalytic effect on the hydrolysis of 4-nitrophenyl esters of tetracoordinated phosphorus acids. The favorable effect of amphiphilic additives is due to their ability to form in aqueous solutions individual and mixed aggregates, the transition of reagent from the mass of solution into these aggregates, and the course of the chemical process in the new phase. The presence of La(III) ions enhances the catalytic effect of calixarene aggregates due to complex manifestations of micellar and homogeneous (electrophilic) catalyst, and to favorable changes in the characteristics (the degree of binding of counterions and surface charge) of the macrocycle aggregates.

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