REACTIVITY IN MICELLES – ARE WE REALLY ABLE TO DESIGN MICELLAR CATALYSTS?

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Coordination of lipophilic alkyl pyridin-2-yl ketoximes **1** to Ni^{2+} ions, reduction of lipophilic 3-alkoxyacetophenones **2** with sodium borohydride, and alkaline hydrolysis of 4-nitrophenyl diphenyl phosphate (PNPDPP) were employed as probes in the investigation which factors may influence the reactivity of organic compounds in micellar systems. In all these reactions, a lipophilic substrate solubilized in micellar core was attacked by a hydrophilic reagent from the bulk aqueous phase. To evaluate the contribution of electrostatic interactions between the micellar surface charge and the reagent to the observed reactivity, we combined reactions involving the reagents with opposite polarity (Ni^{2+} cations and borohydride or hydroxide anions) with positively charged micelles of hexadecyltrimethylammonium chloride (CTAC) or bromide (CTAB) and negatively charged micelles of sodium dodecyl sulfate (SDS). Non-ionic micelles (Triton X-100 or Brij 35) served as a reference. The results of the kinetic studies give evidence that each of the investigated systems has unique properties going in particular aspects beyond the scope of the generally accepted concepts of reactivity in micelles.

Keywords: Cationic micelles; Anionic micelles; Non-ionic micelles; Micellar catalysis; Coordination; Borohydride reduction; Alkaline hydrolysis; Oximes; Hydrolysis; Phosphates.

The phenomenon of micellar catalysis has been extensively studied in the course of the past four decades[1]. Nevertheless, the number of currently published papers and reviews[2] dealing with reactions performed in micelles and microemulsions gives evidence that this research area has still been an evergreen in colloid chemistry. The substance of micellar catalysis lies in bringing together the reactants in a small volume of colloid particle – micelle, inverse micelle, vesicle, or in an oil or water droplet in o/w or w/o microemulsions. The surface charge of ionic micelles can also attract ionic reagents from the bulk aqueous phase, thus increasing their concentration at the boundary of the nanoaggregate[1f]. The inverse case, i.e. the separation of the lipophilic reactant solubilized in a colloid particle from ionic reagents

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by coulombic repulsion, called micellar inhibition, occurs also in many instances. Thus, the phenomenon of micellar catalysis is predominantly a result of an increase in the effective concentration of reactants. Therefore, Romsted and Bunton[3] pertinently branded micellar catalysis as a useful misnomer.

Colloid particles (micelles, vesicles, or microemulsions) can be doped by reactive functional surfactants or metallosurfactants. Such systems often exhibit remarkable reactivity to various substrates and are considered as enzyme mimics. Among them, models of hydrolytic enzymes have been of considerable interest[1e,1g,4]; investigation of hydrolytic micellar catalysts has been stimulated by the need for agents for fast and efficient hydrolysis of neurotoxic organophosphates under mild conditions[4,5]. Much effort has been spent on attempts to increase the efficiency of such systems; the research has been focused predominantly on the reactive function design and on optimization of colloid system properties[1,2,4,5].

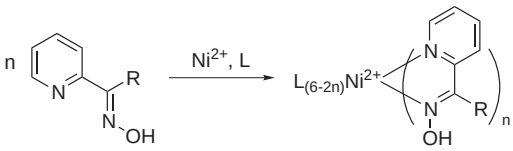
Kinetic data obtained from the reactions performed in nanoaggregates under pseudo-first-order conditions can be treated by the pseudophase models[1c,1d]. Ion exchange between the Stern layer and bulk aqueous phase in the case of ionic micelles is involved in the pseudophase ion-exchange model[1f].

However, despite the fact that we understand basic principles of micellar catalysis and that we are able to fit experimental kinetic data using the above-mentioned models, we are still far from a rational design of micellar catalysts. The problem lies in the fact that micelles are dynamic aggregates with low degree of organization of surfactant molecules and with indefinite phase interface[6]. The behavior of micelles depends on the type of surfactant, its concentration, temperature, concentration of electrolytes present in the system, etc. No doubt, dynamic character of micelles affects mass exchange between the aggregate ("nanoreactor") and the bulk phase as well as the location and orientation of the solubilized organic molecules. Consequently, when studying organic reactions in colloid systems, we usually observe various additional factors affecting the reactivity in particular cases; all these factors are subtle and hard to predict. For example, we have recently found a relationship between the structure and lipophilicity of isomeric amphiphilic pyridinium ketoximes and their ability to hydrolyze phosphates in micellar solutions. We concluded that the observed relationship is a consequence of the location of pyridinium salts and orientation of their molecules in micelles[7].

A great interest in the nanoaggregates dynamics, mass exchange between the bulk phase and colloid particles and location of the reactants is well

documented by the number of papers dealing with these topics. In addition to a theoretical approach represented by various mathematical models of solubilization and mass exchange in colloid systems[8], several analytical methods have been employed as tools in this research, the most important being time-resolved luminescence quenching[9] and measurement of relaxation times in NMR [10]. However, the results and conclusions ensuing from these studies are not yet an applicable tool in the design of micellar catalysts. Another approach to the investigation of interactions between a colloid particle and solubilized reactants is kinetic studies of various model reactions used as probes into nanoaggregates[11]. The advantage of this approach consists in more straightforward interpretation of the obtained results; however, their generalization is more difficult.

In the course of our previous studies focused on hydrolytic activity of metallomicellar catalysts based on chelates of various lipophilic alkyl heteroaryl ketoximes[12] we observed that the rate of coordination of lipophilic alkyl pyridin-2-yl ketoximes **1** to Ni^{2+} ions (Scheme 1) in hexadecyltrimethylammonium bromide (CTAB) micelles is extremely slow compared with analogous reactions with other transition metal ions. This phenomenon cannot be explained simply by coulombic repulsion between Ni^{2+} ions and positive surface charge of CTAB micelles since the formation of Cu^{2+} complexes under the same conditions proceeds immediately. Most probably, slow complexation of Ni^{2+} ions with lipophilic ligands **1** ensues from the geometry of the resulting complex which disfavours its formation at the water/organic phase interface as well as at the boundary of the colloid particle[13].



	R
1a	*n*-C_6H_{13}
1b	*n*-C_7H_{15}
1c	*n*-C_8H_{17}
1d	*n*-C_9H_{19}
1e	*n*-$C_{10}H_{21}$
1f	*n*-$C_{16}H_{33}$

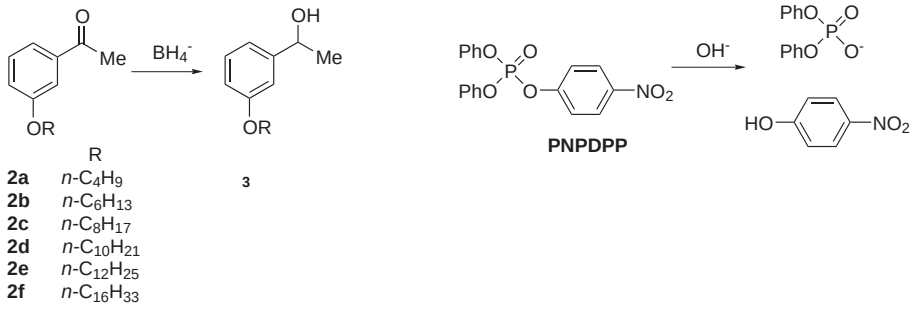
n = 2, 3

L = H_2O or some of the anions present in the system

SCHEME 1

The high sensitivity of the observed rate of coordination of **1** to Ni^{2+} ions in micelles to the lipophilicity of the ligand inspired us to use this reaction as a probe in the investigation of the influence of the type of micellar sys-

tem on the course of organic reactions. For that purpose we decided to study the kinetics of this complexation in cationic, anionic, and non-ionic micellar systems prepared from the most frequently used surfactants CTAB, sodium dodecyl sulfate (SDS), and Triton X-100 (4-(1,1,3,3-tetramethylbutyl)phenyl–oligo(ethylene glycol); n = 9, 10). In the next series of experiments we planned to switch the polarity of coulombic interactions between micelles and the hydrophilic reagent in the bulk aqueous phase. As model reactions to be performed in CTAB, SDS, and Triton X-100 or Brij 35 (poly(ethylene glycol) dodecyl ether; n ~ 23) micelles, we chose the reduction of lipophilic 3-alkoxyacetophenones **2** with sodium borohydride and alkaline hydrolysis of 4-nitrophenyl diphenyl phosphate (PNPDPP) (Scheme 2). We expected these experiments to help to estimate the contribution of coulombic forces to the overall observed effect of micelles on the reaction rate; the reactions carried out in non-ionic micelles (Triton X-100 or Brij 35) should serve as a reference.



SCHEME 2

RESULTS AND DISCUSSION

Model Compounds Used in the Study

Alkyl pyridin-2-yl ketoximes **1** and PNPDPP were prepared previously for other studies[13,14]. 3-Alkoxyacetophenones **2** were prepared analogously to the procedure described in the literature[15] by alkylation of 3-hydroxyacetophenone sodium salt with corresponding alkyl bromide (Scheme 3). The prepared substances gave ^{1}H NMR spectra which were in accordance with the published data[16]. The following requirements were taken into consideration in the design of ketones **2**: (i) the possibility of tuning their lipophilicity, (ii) the possibility to monitor the course of their reduction by

UV spectrophotometry. 3-Alkoxyacetophenones **2** meet both requirements: their lipophilicity can be controlled by the hydrophobic alkyl chain length and the bands in UV spectra of ketones **2** and the resulting secondary alcohols **3** do not overlap as shown on the example of ketone **2f** (absorption maxima at 250 and 309 nm in all investigated micellar systems) and alcohol **3f** (absorption maxima at 280 and 273 nm in all investigated micellar systems). An authentic sample of alcohol **3f** was prepared by the reduction of ketone **2f** with sodium borohydride. The requirement for the possibility of monitoring the reduction by UV spectroscopy excluded the isomeric 4-alkoxyacetophenones since both the ketones and the alcohols, their reduction products, were expected to have practically identical absorption maxima in UV spectra[17]. The same problem can be assumed with their ortho isomers possessing similar electron distribution.

	R
2a	*n*-C_4H_9
2b	*n*-C_6H_{13}
2c	*n*-C_8H_{17}
2d	*n*-$C_{10}H_{21}$
2e	*n*-$C_{12}H_{25}$
2f	*n*-$C_{16}H_{33}$

SCHEME 3

*Coordination of Alkyl Pyridin-2-yl Ketoximes **1** to Ni^{2+} Ions in Micellar Solutions*

Job plots performed with Ni^{2+} ions and ketoximes **1** give evidence that the metal ion:ligand stoichiometry in the complexes formed in all of the examined micellar solutions is 1:2. The absorbances were measured at the absorption maximum of the resulting chelate which ranged from 338 to 342 nm in the investigated micellar systems. All the prepared mixtures were left to stand for 5 h after mixing the reactants to ensure the attainment of equilibrium. As an example, Job plots for ketoxime **1b** in various types of micelles are shown in Fig. 1.

The kinetics were measured at pH 6.3 (0.05 M 2-(*N*-morpholino)ethanesulfonic acid (MES) buffer) and 25 °C with an excess of Ni^{2+} (c_{Ni2+} = 5.0 × 10^{-4} mol l^{-1}) with respect to ligand **1** (c_1 = 1.0 × 10^{-4} mol l^{-1}). The course of the coordination was monitored by measuring the UV absorbance of the resulting complex in the reaction mixtures. Regardless of the alkyl chain length, the rate of Ni^{2+} complexation with ketoximes **1** in anionic micelles of SDS was very fast and we were not able to follow the reactions even by the stopped-flow method with the scanning time of 12.5 ms (allowing the

determination of the first-order rate constants up to 20 s^{-1}). In cationic micelles of CTAB and non-ionic micelles of Triton X-100 we were able to follow the kinetics of complexation of ligands **1** with hydrophobic alkyl chain length C_4 and longer.

The only bands observed in UV spectra of the reaction mixtures were those of the starting ketoxime **1** and the resulting 1:2 complex. The overlaid UV spectra of the reaction mixture recorded in any kinetic run were intersected in an isosbestic point thus giving the evidence that the 1:1 complex is formed in a pre-equilibrium step while the formation of the 1:2 complex is the rate-determinning step of this reaction sequence (Scheme 4; L stands for ketoxime **1**). The proposed kinetic scheme is in accordance with the assumption that the coordination of more than one molecule of lipophilic bidentate ligand to Ni^{2+} ion is disfavoured if it proceeds at the aqueous/organic phase interface[13]. Scheme 4 disregards the acid-base equilibria.

$$Ni^{2+} + L \underset{k_{-1}}{\overset{k_1}{\rightleftharpoons}} NiL^{2+}$$

$$NiL^{2+} + L \xrightarrow{k_2} NiL_2^{2+}$$

SCHEME 4

Assuming the applicability of the Bodenstein steady-state approximation for the 1:1 complex of ketoxime **1** and Ni^{2+}, we get Eq. (*1*). The rate of the 1:2 complex formation is described by Eq. (*2*). Combining Eqs (*1*) and (*2*) we obtain Eq. (*3*). Excess of Ni^{2+} ions allows to simplify Eq. (*3*) to Eq. (*4*) ($k_2 k_1[Ni^{2+}] = k'$).

$$k_1[Ni^{2+}][L] = k_{-1}[NiL^{2+}] + k_2[NiL^{2+}][L] \qquad (1)$$

$$d[NiL_2{}^{2+}]/d\tau = k_2[NiL^{2+}][L] \qquad (2)$$

$$d[NiL_2{}^{2+}]/d\tau = k_2 k_1[Ni^{2+}][L]^2/(k_{-1} + k_2[L]) \qquad (3)$$

$$d[NiL_2{}^{2+}]/d\tau = k'[L]^2/(k_{-1} + k_2[L]) \qquad (4)$$

If $k_{-1} << k_2[L]$ (this condition can be assumed at higher ligand concentrations), the second-order kinetics (Eq. (*4*)) can be approximated by the

pseudo-first-order kinetics (Eqs (*5*) and (*6*); $[L_0]$ stands for the initial concentration of ketoxime **1**).

$$d[NiL_2^{2+}]/d\tau = k[L] \quad (5)$$

$$d[NiL_2^{2+}]/d\tau = k([L_0] - 2\,[NiL_2^{2+}]) \quad (6)$$

Therefore, first we attempted to fit the obtained absorbance-versus-time data (up to 60% conversion) using the pseudo-first-order kinetic model. The fact that the fit error did not exceed 3% in any case verified that the above-mentioned approximation was correct.

Not surprisingly, the observed pseudo-first order rate constant k_{obs} values decrease with increasing surfactant concentration (and, consequently, dilution of the ligand in micellar phase) as shown on the example of ligand **1b** coordination in CTAB micelles (Fig. 2a). Nevertheless, the effective rate constants k_{eff} taking into account real concentrations of the reactants solubilized in micelles[18] (Fig. 2b) were practically independent of the surfactant concentration c_{surf}. Effective rate constants k_{eff} can be calculated from the observed rate constants k_{obs} using Eq. (*7*)

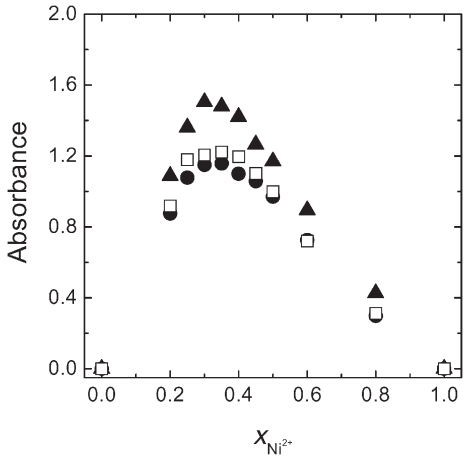


FIG. 1
Coordination of ligand **1b** to Ni^{2+} ions in micelles of CTAB (●), SDS (□), and Triton X-100 (▲) – Job plots. Conditions: pH 6.3 (0.05 M MES buffer), 25 °C, concentration of the surfactants $c_{surf} = 1.0 \times 10^{-2}$ mol l^{-1}. Concentrations c_{Ni2+} of the Ni^{2+} ions and c_{1c} of the ligand: $c_{Ni2+} + c_{1c} = 8.0 \times 10^{-4}$ mol l^{-1}

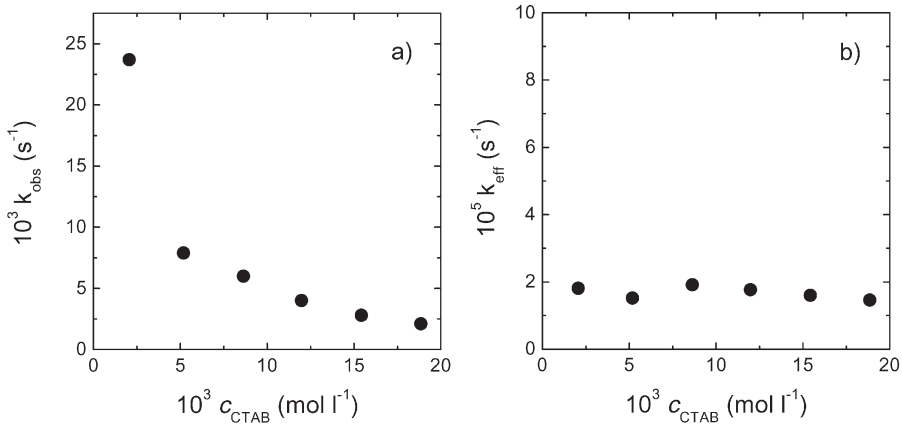


FIG. 2

Coordination of ligand **1b** to Ni^{2+} ions in CTAB micelles. Dependence of the observed pseudo-first-order rate constant k_{obs} a) and the effective rate constant k_{eff} b) on CTAB concentration. Conditions: pH 6.3 (0.05 M MES buffer), 25 °C, $c_{Ni2+} = 5.0 \times 10^{-4}$ mol l^{-1}, $c_1 = 1.0 \times 10^{-4}$ mol l^{-1}

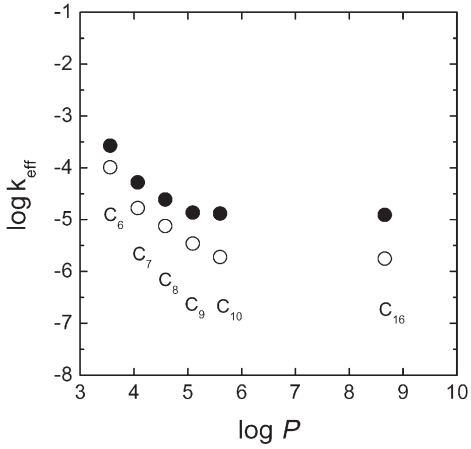


FIG. 3

Coordination of ligands **1** to Ni^{2+} ions in CTAB (○) and Triton X-100 (●) micelles. Dependence of the effective rate constant k_{eff} on the lipophilicity of ligand **1**. Conditions: pH 6.3 (0.05 M MES buffer), 25 °C, $c_{Ni2+} = 5.0 \times 10^{-4}$ mol l^{-1}, $c_1 = 1.0 \times 10^{-4}$ mol l^{-1}, $c_{CTAB} = 5.0 \times 10^{-3}$ mol l^{-1}, $c_{Triton} = 4.0 \times 10^{-4}$ mol l^{-1}

$$k_{\text{eff}} = k_{\text{obs}}\, c_{\text{surf}}\, (V_{\text{M}})_{\text{surf}} \qquad (7)$$

where $(V_{\text{M}})_{\text{surf}}$ stands for the molar volume of the micellized surfactant and other symbols have the above-defined meaning. The advantage of the effective rate constants k_{eff} consists in the fact that they are independent of the surfactant concentration unless the increased concentration of the surfactant causes changes in the type of the aggregate. Hence, using k_{eff}, it is possible to compare reactions performed in systems of different concentrations of the micelle-forming surfactant. The molar volume values used in this study were taken over from Scrimin et al.[18] for CTAB, Brij 35, and Triton X-100 ($(V_{\text{M}})_{\text{CTAB}}$ = 0.37 l mol^{-1}, $(V_{\text{M}})_{\text{Brij}}$ = 1.1 l mol^{-1}, $(V_{\text{M}})_{\text{Triton}}$ = 0.5 l mol^{-1}) and from Vass et al.[19] for SDS ($(V_{\text{M}})_{\text{SDS}}$ = 0.25 l mol^{-1}).

The dependence of the effective rate constants k_{eff} on the lipophilicity of ligand **1** in CTAB and in Triton X-100 micelles is shown in Fig. 3. Partition coefficients P of ketoximes **1** between octan-1-ol and water were used as a generally accepted measure of lipophilicity; their values were predicted using a software package[20] Pallas 1.2. Both in CTAB and in Triton X-100, the k_{eff} values decrease with increasing lipophilicity of the ligand **1** reaching a plateau at log P values around 5.5, corresponding to C_{10} alkyl chains. We assume that in the plateau region ligands **1** are almost completely solubilized in micellar core and the reaction rate is controlled by the diffusion of Ni^{2+} ions through a Stern layer in the case of CTAB or through a palisade layer of oligo(oxyethylene) chains in the case of Triton X-100. The increase in the complexation rates observed for lower homologues gives evidence that the ligands of lower lipophilicity can more easily cross the interface between the micellar pseudophase and bulk aqueous phase and adopt the arrangement suitable for complex formation.

Considering the complexation in non-ionic micelles of Triton X-100 as a reference, the reaction rate enhancement caused by the negative micellar surface charge on the one hand, and the deceleration of the reaction due to the positive micellar surface charge on the other hand, are vastly different. While the complexation in anionic SDS is faster by more than six orders of magnitude than complexation in Triton X-100, the difference between non-ionic Triton X-100 and cationic CTAB is less than one order of magnitude only.

*Reduction of 3-Alkoxyacetophenones **2** with Sodium Borohydride in Micellar Solutions*

In the next part of this study we have focused on reductions of lipophilic 3-alkoxyacetophenones **2** with sodium borohydride in CTAB, SDS, and Brij 35. The aim of these experiments was to switch the polarity of coulombic interactions between micelles and a hydrophilic reagent located in the bulk aqueous phase. Hitherto, micellar systems have been used as a reaction medium for borohydride reductions in several instances[21,22]. Although cationic micelles have been expected to facilitate these reactions due to coulombic attraction between the reagent and the micellar surface[21b], the reactivity of sodium borohydride has also been examined in the aggregates of anionic[21c] and non-ionic[21c] surfactants. However, the published data do not allow direct evaluation of the micellar surface charge effect on the observed reactivity.

The obtained results for acetophenones **2** reductions with sodium borohydride were somewhat surprising. The effective rate constants k_{eff} obtained in CTAB micelles were lower than those found in non-ionic Brij 35 (Fig. 4). It is evident that these results are in contradiction with the antici-

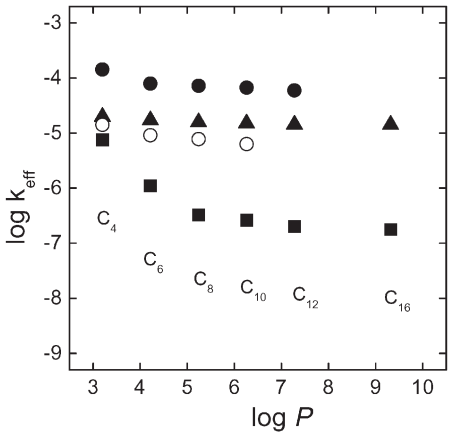


FIG. 4

Reduction of ketones **2** with $NaBH_4$ in SDS (■), CTAB (▲), Brij 35 (●), and with $Me_4N^+BH_4^-$ in Brij 35 (○). Dependence of the effective rate constant k_{eff} on the lipophilicity of ketone **2**. Conditions: pH 12.3 (1.9×10^{-2} M NaOH), 25 °C, $c_{NaBH4} = 6.25 \times 10^{-3}$ mol l^{-1}, $c_2 = 1.0 \times 10^{-4}$ mol l^{-1}, $c_{CTAB} = 1.00 \times 10^{-2}$ mol l^{-1}, $c_{Brij} = 5.00 \times 10^{-3}$ mol l^{-1}, $c_{SDS} = 5.00 \times 10^{-2}$ mol l^{-1}. The k_{eff} value for ketone **2f** in Brij 35 was not determined due to low solubility of the substrate in the reaction mixture

pated coulombic attraction between the positive surface charge of CTAB micelles and the negatively charged borohydride anion.

First, we assumed the formation of alkoxyborohydrides of general formula $[C_{12}H_{25}(OCH_2CH_2)_{23}O]_nBH_{4-n}^-$ (n = 1–3) in the reaction system. These species were expected to be formed by the reaction of borohydride anion with terminal hydroxy group[23] of Brij 35. Alkoxyborohydrides $[C_{12}H_{25}(OCH_2CH_2)_{23}O]_nBH_{4-n}^-$ representing surfactants with a covalently bound reductive function could increase the observed reactivity of the system. However, in ^{11}B NMR spectra of the 0.01 M sodium borohydride solution in 0.1 M sodium hydroxide and 0.1 M Brij 35 (the concentrations of borohydride anion and Brij 35 were increased adequately to enable NMR experiment) measured within the interval of 10 h we did not find any other signal except those of the starting borohydride anion (42.1, qi, J_{BH} = 80 Hz) and of borate anion (1.3, s), the final product of the borohydride anion degradation. Moreover, the kinetics of the ketones **2** reductions do not exhibit any induction period corresponding to the initial formation of alkoxyborohydrides (all the reaction mixture components, i.e. sodium borohydride, Brij 35, and ketone **2** were mixed just before starting the reaction in all cases).

Another plausible explanation of higher reaction rate in non-ionic micelles lies in non-covalent binding of sodium borohydride to oligoethylene chains of Brij 35. Ion-pair extractions by oligo(ethylene glycols) or by their monoalkyl ethers have been widely utilized in phase-transfer catalysis[24] (oligo(ethylene glycols) are sometimes named as "poor chemist's crowns"[24c]). If it was really extraction of sodium borohydride from bulk aqueous phase by oligoethylene chains of Brij 35 which increased the rate of the ketones **2** reduction, this reaction should be markedly decelerated by replacing sodium for any cation which cannot be coordinated. To verify this assumption, we also performed reductions of ketones **2** with tetramethylammonium borohydride in tetramethylammonium hydroxide under analogous conditions. As shown in Fig. 4, the cation replacement led indeed to a reaction rate decrease approximately by one order of magnitude. Hence, non-ionic micelles seem to facilitate reductions of ketones **2** with sodium borohydride due to the reducing agent extraction into micellar pseudophase. Potential applications of this phenomenon will be a topic of further research.

As expected, the reduction of ketones **2** in SDS micelles was markedly slower compared with the reactions performed in CTAB and Brij 35.

If all the individual components of the reaction system (SDS solution, solution of the substrate, and alkaline solution of sodium borohydride)

were mixed at zero time of the reaction we observed an induction period of ca. 2 h as evident from the example of the ketone **2e** reduction (Fig. 5a). Therefore, the kinetics of the ketones **2** reductions were followed after the injection of a substrate solution into micellar systems of SDS and sodium borohydride prepared 10 h before the reaction. In these instances the absorbance-versus-time data followed the first-order kinetics (Fig. 5b): these data were used for the calculation of k_{eff} values given in Fig. 4.

The absorbance-versus-time data obtained from reductions of ketones **2** in SDS micelles (Fig. 5) give evidence that the borohydride anion interacts with SDS forming a reducing agent bound to the nanoaggregate. Due to the repulsive coulombic forces between the borohydride and dodecyl sulfate anions it seems unlikely that sodium borohydride is bound to SDS micelles by any kind of non-covalent interaction. Despite very low nucleophilicity of dodecyl sulfate anion it is reasonable to assume that species of general formula $[C_{12}H_{25}OSO_2O]_nBH_{4-n}^-$ might be formed under the reaction conditions. The existence of a similar type of compounds (sulfonatoboranes) has already been reported[25]. Similarly as in the case of Brij 35 we followed the fate of borohydride anion in SDS micelles by means of ^{11}B NMR spectroscopy. However, as in the previous case we did not find any other signal except those of borohydride and borate anions. Thus, the above-stated explanation of the observed induction period is only speculative.

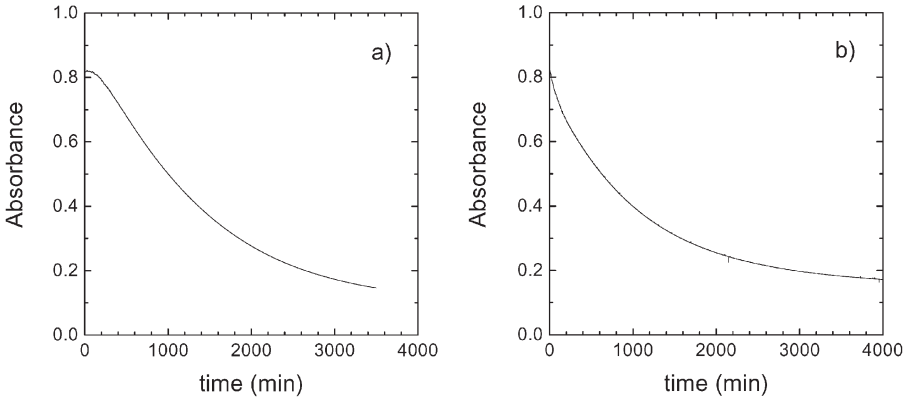


FIG. 5

Reduction of ketones **2e** with $NaBH_4$ in SDS micelles – typical examples of the reaction course. a) All the components of the reaction system were mixed at zero time of the reaction. b) Ketone **2e** was added to micellar systems of SDS and sodium borohydride prepared 10 h before the reaction. Conditions: pH 12.3 (1.9×10^{-2} M NaOH), 25 °C, $c_{NaBH4} = 6.25 \times 10^{-3}$ mol l^{-1}, $c_{2e} = 1.0 \times 10^{-4}$ mol l^{-1}, $c_{SDS} = 5.00 \times 10^{-2}$ mol l^{-1}

As follows from the aforementioned discussion of the results of ketones **2** reductions in cationic, non-ionic, and anionic surfactants, the behavior of borohydride anion in micellar systems is more complex than it has been expected so far[21,22]. Hence, these reactions can hardly serve as a probe for the investigation of nanoaggregates properties.

Hydrolysis of 4-Nitrophenyl Diphenyl Phosphate (PNPDPP) in Micellar Solutions

The unexpected behavior of the borohydride anion in micellar systems made us to turn our attention to another reaction involving anion as a reagent. Of the reactions being worth of consideration we chose alkaline hydrolysis of 4-nitrophenyl diphenyl phosphate (PNPDPP) for several reasons. This reaction has been used in numerous studies[1–7] as a model for testing the efficacy of micellar catalysts. PNPDPP as a lipophilic compound (log P = 4.7) is expected to be located in micellar core. Consequently, the reaction rate should be controlled by the hydroxide anion concentration at micellar surface and by its transport into micellar interior. We assumed that the pH dependence of the pseudo-first order rate constant k_{obs} of the PNPDPP hydrolysis should allow qualitative evaluation of the micellar surface charge effect on the above-mentioned factors influencing the observed reactivity.

We decided to study the alkaline hydrolysis of PNPDPP in cationic micelles of CTAB and hexadecyltrimethylammonium chloride (CTAC), in non-ionic micelles of Triton X-100 and Brij 35, and in anionic micelles of SDS. In all instances, the surfactant concentration was a double of the published critical micelle concetration[26]. Modified Britton–Robinson buffers were used to set the pH values in reaction mixtures. Their concentration (0.1 mol l^{-1}) was high enough to maintain pH in the bulk aqueous phase even if all the halide anions of cationic surfactants were exchanged for hydroxide anions. In all cases, the course of the PNPDPP hydrolysis was monitored by UV spectrophotometry, monitoring the concentration of the resulting 4-nitrophenol.

The obtained pH dependences of the observed rate constants k_{obs} are shown in Fig. 6. For comparison, the pH dependence of alkaline hydrolysis of PNPDPP in homogeneous aqueous solution is included as well; the dependence was calculated using the published[27] second-order rate constant (0.4 l mol^{-1} s^{-1}).

As expected, the PNPDPP hydrolysis was inhibited in SDS micelles and the highest reaction rates were observed in cationic surfactants.

Both in CTAB and in CTAC, the observed log k_{obs} vs pH dependence is flat up to pH 10. In the pH range from 7 to ~9.5 there is even a plateau where the rate of PNPDPP hydrolysis is independent of the hydroxide anion concentration. Hence, cationic micelles behave as anion exchangers maintaining the local pH in the Stern layer at practically constant value – in the span of six pH units (5–11), the observed rate constant k_{obs} value increases only by one order of magnitude. At higher pH values the "buffering" capacity of the surfactant cationic head groups is exhausted and the slope of the log k_{obs} vs pH dependence is approximately unity, just as in the case of the reaction in homogeneous aqueous solution.

Under slightly alkaline conditions (pH < 9.5), the PNPDPP hydrolysis in non-ionic micelles of Triton X-100 and Brij 35 is slower than that in cationic micelles but faster than the reaction in homogeneous aqueous solution. Most probably, the rate enhancement in comparison with homogeneous reaction results from the increased effective PNPDPP concentration in micellar pseudophase. The log k_{obs} vs pH dependence is almost linear; its slope is low (ca. 0.2) thus giving evidence of the resistance of the oligo(oxyethylene) chain palisade to the hydroxide anion transport. This resistance seems to be broken at pH around 10; at higher pH, the rates of

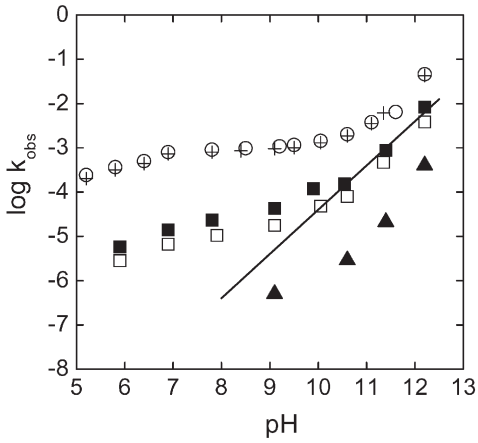


FIG. 6

Alkaline hydrolysis of PNPDPP – pH dependence of the observed rate constant k_{obs} in SDS (▲), Triton X-100 (□), Brij 35 (■), CTAC (○), and CTAB (+) micelles. Conditions: 25 °C, c_{PNPDPP} = 2.0×10^{-5} mol l^{-1}, $c_{SDS} = 1.6 \times 10^{-3}$ mol l^{-1}, $c_{Triton} = 4.4 \times 10^{-4}$ mol l^{-1}, $c_{Brij} = 2.0 \times 10^{-4}$ mol l^{-1}, $c_{CTAC} = 3.2 \times 10^{-3}$ mol l^{-1}, $c_{CTAB} = 2.0 \times 10^{-3}$ mol l^{-1}. Line: alkaline hydrolysis of PNPDPP in homogeneous aqueous solution (calculated using the published[27] second-order rate constant value)

PNPDPP hydrolysis in non-ionic micelles and in homogeneous aqueous solutions are practically the same.

In contrast with coordination of ketoximes **1** to Ni^{2+} ions, the effect of coulombic attraction or repulsion on the observed rate of the PNPDPP hydrolysis in micellar systems is comparable, considering the reactivity in non-ionic micelles as a reference.

It is worthy to mention an unusual course of the PNPDPP hydrolysis observed in Brij 35 at pH below 10. As evident from the example given in Fig. 7, the hydrolysis was very fast up to 25–30% conversion. Then, the reaction rate decreased substantially. At the second stage of the hydrolysis the absorbance-versus-time data followed the first-order kinetics; these data were used for the calculation of the rate constants given in Fig. 6. So far we have had no plausible explanation of the observed phenomenon. Most likely, its substance lies in the depth of the oligo(oxyethylene) chain palisade of Brij 35 micelles which is higher by a factor of ~2 compared with Triton X-100. Since the reactions were started by the injection of a substrate solution into a buffered surfactant solution, the fast initial stage of the hydrolysis might indicate slow transport of PNPDPP into micellar core. Localized in the oligo(oxyethylene) chain palisade, PNPDPP can be more easily attacked by hydroxide anions.

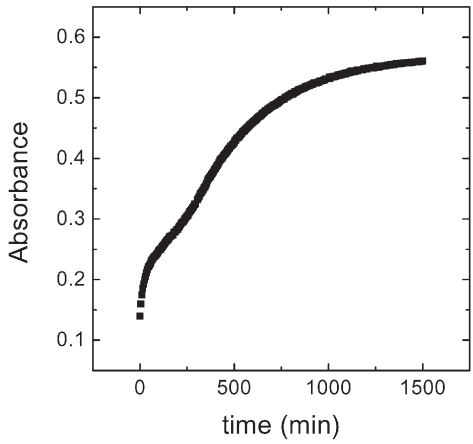


FIG. 7
The course of alkaline hydrolysis of PNPDPP in Brij 35 at pH 9.0. Conditions: 25 °C, c_{PNPDPP} = 2.0×10^{-5} mol l^{-1}, c_{Brij} = 2.0×10^{-4} mol l^{-1}

Conclusion

The current study represents an attempt to evaluate the influence of properties of the interface between the bulk aqueous phase and micellar pseudophase on the course of chemical reactions. We tried to utilize various chemical reactions as probes into the most frequently used types of micelles. The results of the performed kinetic studies demonstrated that each of the investigated systems has unique properties going in particular aspects beyond the scope of generally accepted concepts of reactivity in micelles assuming only the effect of the increased local concentration of reactants and the effect of coulombic forces. For example, considering the reactivity in non-ionic micelles as a reference, the apparent effect of the micellar surface charge on the reaction rate varies markedly from case to case. This fact indicates that the contribution of coulombic forces between the micellar surface and the reagent approaching the aggregate may be overestimated in many cases and that the observed reactivity in micelles can be strongly influenced by various other factors.

Thus, being used as a reaction medium, micellar solutions may provide considerable benefits in comparison with homogeneous solutions in particular cases; however, the tools for a rational design of micellar catalysts are still limited.

EXPERIMENTAL

General

The temperature data were uncorrected. ^{1}H NMR spectra were recorded on a Varian Mercury Plus 300 spectrometer operating at 299.97 MHz for ^{1}H. Chemical shifts (δ) in ppm are reported relative to Me_4Si as internal standard. All coupling constants (*J*) are in Hz. TLC analyses were carried out on DC Alufolien Kieselgel 60 F254. Preparative column chromatography was performed on silica gel 60, 0.040–0.063 mm. Kinetic measurements were performed with a Hewlett–Packard HP 8452 spectrophotometer with a thermostatted multicell transport cell holder HP 89075C or with Varian Cary 50 UV-VIS equipped with a thermostatted multicell transport cell holder in 1-cm spectrophotometric cells.

Chemicals

All the chemicals used in the syntheses (purum or pract.) were used as received. The solvents were purified and dried using the described procedures[28]. 4-Nitrophenyl diphenyl phosphate (PNPDPP) and alkyl pyridin-2-yl ketoximes **1** were prepared previously[12d,13]. Hexadecyltrimethylammonium bromide (CTAB) puriss., hexadecyltrimethylammonium chloride $(CTAC)_i$ 25 wt.% solution in water were obtained from Aldrich, Triton X-100 from Fluka, and Brij 35, 30 wt.% solution in water from Sigma. 2-(*N*-Morpholino)ethane-1-sulfonic acid (MES) was purchased by Sigma. Nickel(II) nitrate (analytical grade) was the

product of Lachema Brno; its concentration in stock solutions was determined by EDTA titration following standard procedure[29].

1-(3-Hexadecyloxyphenyl)ethanol **3f**

Sodium borohydride (100 mg, 2.64 mmol) was added in several portions over 0.5 h into a solution of 3-(hexadecyloxy)acetophenone (**2f**) (250 mg, 0.7 mmol) in the mixture of ethanol (10 ml) and tetrahydrofurane (2 ml). The reaction mixture was stirred at room temperature overnight; the completion of the reaction was checked by TLC (dichloromethane). Then, the solvents were evaporated, water (5 ml) was added to the obtained residue and the product was extracted into dichloromethane (2 × 3 ml). The combined extracts were washed with water (5 ml) and dried with magnesium sulfate. The crude product obtained after the evaporation of the solvent was purified by column chromatography (dichloromethane–toluene 1:1). Yield 190 mg (76%), white crystals. M.p. 39–40 °C. ^{1}H NMR ($CDCl_3$): 0.88 t, 3 H, J(16′,15′) = 6.6 (CH_3); 1.26 bs, 24 H $(CH_2)_{12}$; 1.45 m, 2 H (3′-CH_2); 1.49 d, 3 H, J(2,1) = 6.3 (CH(OH)C**H**$_3$); 1.78 m, 2 H (2′-CH_2); 3.96 t, 2 H, J(1,2) = 6.6 (OCH_2); 4.86 qa, 1 H, J(1,2) = 6.3 (C**H**(OH)CH_3); 6.80 d, 1 H (ArH); 6.90–6.98 m, 2 H (ArH); 7.25 m, 1 H (ArH). For $C_{24}H_{42}O_2$ (362.6) calculated: 79.50% C, 11.67% H; found: 79.29% C, 12.08% H. UV, λ_{max}: 280 and 273 nm in all investigated micellar solutions under the conditions given in the caption to Fig. 4.

Coordination of Alkyl Pyridin-2-yl Ketoximes **1** to Ni^{2+} Ions

Reaction mixtures were prepared directly in spectrophotometric cells by mixing the appropriate amounts of micellar solution of ligand **1** in CTAB, Triton X-100 or SDS, re-destilled water, and aqueous buffer solution. The cells were thermostatted for 20 min in the cell holder to 25.0 ± 0.1 °C. The reactions were initiated by the addition of an appropriate amount of 5.0×10^{-2} M aqueous solution of nickel(II) nitrate. No changes in pH were observed during the kinetic runs. The reactions were monitored at the maximum of the resulting complex absorption (from 338 to 342 nm). The pseudo-first-order rate constants k_{obs} were obtained by non-linear regression analysis of the absorbance-versus-time data up to 60% conversion using the equation $A_t = (A_{inf} - A_0)[1 - \exp(-kt)] + A_0$. Regression analysis was performed using program Origin 6.1 (ref.[30]). In all cases, the correlation coefficient $r >$ 0.999. The kinetic runs were performed in duplicate and the rate constants were calculated as a mean of the values obtained from these parallel determinations. The differences between these results did not exceed 5%.

Reduction of 3-Alkoxyacetophenones **2** with Sodium Borohydride

Reaction mixtures were prepared directly in spectrophotometric cells by mixing an appropriate amount of the surfactant solution, freshly prepared 0.1 M $NaBH_4$ solution in 0.3 M NaOH, and water. The cells were thermostatted for 20 min in the cell holder to 25.0 ± 0.1 °C. In the case of SDS, micellar solutions of sodium borohydride were prepared 10 h before starting the reaction. The reaction was initiated by the addition of appropriate amount of 0.01 M solution of ketone **2** in acetonitrile into spectrophotometric cell. The reactions were monitored at the maximum absorption of ketone **2** (308 nm). The pseudo-first-order rate constants k_{obs} were obtained by nonlinear regression analysis of absorbance-versus-time data using the equation $A_t = A_0 \exp(-kt) + A_0$. Regression analysis was performed using program

Origin 6.1 (ref.[30]). In all cases, the correlation coefficient $r > 0.999$. The kinetic runs were performed in duplicate and the rate constants were calculated as a mean of the values obtained from these parallel determinations. The differences between these results did not exceed 5%.

Hydrolysis of 4-Nitrophenyl Diphenyl Phosphate (PNPDPP)

Reaction mixtures were prepared directly in spectrophotometric cells by mixing of an appropriate amount of an aqueous surfactant solution, buffer, and water. The cells were thermostatted for 20 min in the cell holder to 25.0 ± 0.1 °C. The reactions were initiated by the addition of appropriate amount of 5.0×10^{-3} M PNPDPP solution in acetonitrile. No changes in pH were observed during the kinetic runs. The reactions were monitored at the maximum absorption of the resulting 4-nitrophenoxide anion (400 nm) or, in the case of reactions performed at pH below 6.5, at 317 nm (maximum of 4-nitrophenol absorption). The pseudo-first-order rate constants k_{obs} were obtained by nonlinear regression analysis of the absorbance-versus-time data using the equation $A_t = (A_{inf} - A_0)[1 - \exp(-kt)] + A_0$. Regression analysis was performed using program Origin 6.1 (ref.[30]). In all cases, the correlation coefficient $r > 0.999$. The kinetic runs were performed in duplicate and the rate constants were calculated as a mean of the values obtained from these parallel determinations. The differences between these results did not exceed 5%.

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