J. Org. Chem. **1999,** *64,* 5757−5763

Catalysis in Micellar Media. Kinetics and Mechanism for the Reaction of 1-Fluoro-2,4-dinitrobenzene with *n*-Butylamine and Piperidine in *n*-Hexane and AOT/*n*-Hexane/Water Reverse Micelles

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Received September 15, 1998

The nucleophilic aromatic substitution S_NAr reaction of 1-fluoro-2,4-dinitrobenzene with *n*-butylamine and piperidine was studied in *n*-hexane and AOT/*n*-hexane/water reverse micelle media. The kinetic profile of the reactions was investigated as a function of variables such as AOT and the amine concentration and the amount of water dispersed in the reverse micelles, $W_0 = [H_2O]/[AOT]$. The reactions are faster in the micellar medium than in the pure solvent. The overall reactions are accelerated by increasing the AOT concentration until a value of $[AOT] \cong 0.1$ M, where saturation in the micellar interface is reached and no further micellar catalysis is observed. The reactions are base catalyzed in *n*-hexane but not in a micellar medium. Thus, despite the partition of the reactants in both pseudophases the reactions effectively take place at the interface of the aggregates. The kinetic behavior can be quantitatively explained by taking into account the distribution of the substrate and the nucleophile between the bulk solvent and the micelle interface. The results were used to evaluate the amine distribution constant between the micellar pseudophase and organic solvent and the intrinsic second-order rate coefficient of the S_NAr reaction in the interface. A mechanism to rationalize the kinetic results is proposed.

Introduction

Reverse micellar systems are powerful models that have found applications in biological compartmentalization studies, enzymatic catalysis, and separation of biomolecules.[1−3] Undoubtedly, the use of these micelles to solubilize enzymes in organic solvents has attracted great interest and a large variety of enzymes have been successfully encapsulated in reverse micellar systems.[4,5] Also, these micellar systems have been proven very useful to obtain new inorganic materials such as nanocrystallites[6] and polymers under mild conditions.[7]

Two clearly differentiated phases (aqueous and organic) present in reversed micelles allow compartmentalization of solubilized species at the microscopic level. Solubilization of a reactant in the same region of the surfactant assembly can lead to significant acceleration of reaction rates, while the rates of reactions of segregated reactants are retarded. When both reactants are in the water droplet, they are concentrated as in a nanoreactor, and since the size of this reactor is easily varied, the influence of the properties of the micellar system is relatively easy to assess.[6,8]

Among the surfactants that form reverse micelles, the best known are the systems derived from the anionic surfactant Aerosol-OT (sodium bis(2-ethylhexyl) sulfosuccinate, abbreviated AOT) in different nonpolar media. AOT has a well-known V-shaped molecular geometry, giving rise to stable reversed micelles without cosurfactants. The reverse micellar solution can dissolve a large amount of water with the formation of discrete droplet reverse micelles or bicontinuous reverse micelles.[3,6] The size of the droplets depends only on the water concentration defined as the water-to-surfactant molar ratio W_0 ($W_0 = [H_2O/[AOT]$).

Reverse micellar solutions of AOT are optically transparent, and therefore the changes could be followed by different spectroscopic methods. Since both hydrophilic and hydrophobic components could be solubilized, it is possible to study a variety of systems involving both types of substances. Depending on the concentration of surfactant and water, the strength of surfactant−water interaction, the size of the water pool, the microscopic viscosity and the polarity of the aqueous interior control, the properties of the AOT reverse micelle can be changed. The effect of AOT reverse micelles on a wide variety of chemical reactions has been recently reviewed.[3] Presently, the kinetics models that allow interpreting intrinsic reactivity constants in these media are still scarce.[9]

For a number of years we have been interested in bimolecular aromatic nucleophilic substitution (S_NAr) reactions between several nitro substituted aromatic substrates and aliphatic amines in *n*-hexane[10,11] and

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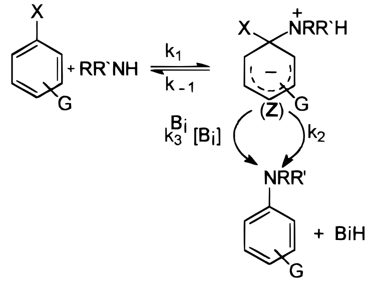
10.1021/jo9818632 CCC: $18.00

other nonpolar[12] and polar aprotic solvents.[13,14] In this work we report a kinetic study of the nucleophilic aromatic substitution S_NAr reaction of 1-fluoro-2,4-dinitrobenzene (FNDB) with *n*-butylamine and piperidine in *n*-hexane and AOT/*n*-hexane/water reverse micelle media. For primary or secondary amines as nucleophiles the general mechanism accepted[15−17] for S_NAr reactions involving halogen or nitrite as leaving groups can be represented by eq 1.



(1)

where R′ could be H or an alkyl group, X is the leaving group, and G stands for electron withdrawing substituents. B_i is the nucleophile or any other base added to the reaction medium. By application of the steady-state hypothesis to this mechanism and in the limiting situation when $k_{-1} \gg k_2 + k_3^{B_i}[B_i]$, eq 2 is obtained, where

$$k_A = k' + k''[B_i] \qquad (2)$$

k_A is the second-order rate constant, $k' = k_1k_2/k_{-1}$ and $k'' = k_1k_3^{B_i}/k_{-1}$. In this case the decomposition of Z is rate limiting and base catalysis may be expected. A linear response to base concentration as depicted in eq 2 is characteristic of the majority of base-catalyzed reactions. On the other hand, if $k_{-1} \ll k_2 + k_3^{B_i}[B_i]$ or more precisely $k_2 \gg k_{-1}$, the formation of the intermediate Z is rate limiting and consequently $k_A = k_1$. Other intermediate situations where curvilinear dependence of k_A with amine concentration may be found.[15−17]

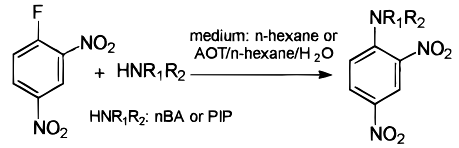
Reverse micellar catalysis for the decomposition of Meisenheimer complexes, the intermediate of S_NAr, was studied in several micellar systems but mostly using cationic surfactants.[18] The S_NAr reaction between glutathione (GSH) and 1-chloro-2,4-dinitrobenzene in reverse micelles of cetyltrimethylammonium bromide (CTAB), AOT, and Triton X-100 in isooctane has been reported.[19] The reaction was performed by controlling the pH, the thiolate ion (GS^-), being the nucleophile. The reaction was 20 times faster in the cationic CTAB micelles than the rate in the aqueous phase or in the Triton X-100 reverse micelles. On the other hand, the reaction rate in AOT was slower than in aqueous solution. The authors conclude that the micellar system with a surfactant with the positively charged head (CTAB) in isooctane mimics the active site of glutathione transferase and is capable of stabilizing the negatively charged Meisenheimer intermediate catalyzing the reaction.

Recent studies of S_NAr in reverse micelles have been reported for the reaction of 1-fluoro-2,4-dinitrofluorobenzene with hydroxide ion[20] in AOT/heptane/water and in benzylhexadecyldimethylammonium chloride (BHDC)/benzene/water. It has also been found that in the cationic micelles the reaction is catalyzed relative to the homogeneous solutions, whereas in the anionic micelles the reaction is inhibited. The catalysis observed is explained by considering that the effective concentration of hydroxide ion at the interface of the cationic micelles is higher than in the anionic one and the reaction is favored.

In this work, we show that the S_NAr reactions between FNDB with either *n*-butylamine or piperidine are faster in the micellar system than in the pure organic solvent. The rate of reactions depends on W_0. The reactions, which are wholly base catalyzed in *n*-hexane, change the mechanism in the micelle interface, the formation of the Z intermediate being the rate-determining step.

Results and Discussion

The reactions of 1-fluoro-2,4-dinitrobenzene (FDNB) with *n*-butylamine (nBA) and piperidine (PIP) in *n*-hexane or in AOT/*n*-hexane/water reverse micelles produce *ipso*-fluorine substitution, giving the corresponding alkylanilines, *N*-butyl-2,4-dinitroaniline and *N*-(2,4-dinitrophenyl)piperidine, respectively (eq 3) in quantitative yields, as shown by UV−visible spectroscopic analysis of the reaction mixture.



(3)

In all cases, the UV−visible spectroscopy analysis at different times shows a clear isosbestic point evidencing the cleanness of the reactions, the rising absorbance being due to the absorption of the product. TLC and HPLC chromatography analyses also show only one product at all times during the reaction. In each case, a large excess of nucleophile was used and the reactions follow pseudo-first-order kinetics.

Reaction in *n*-Hexane. Typical kinetic results are shown in Figure 1 and Table 1. As can be inferred, reaction rates increase with amine concentrations (Figure 1), following a kinetic law given by eq 4, where k_{obs} is

$$k_{obs} = k'[Am] + k''[Am]^2 \qquad (4)$$

the observed pseudo-first-order constant, [Am] is the corresponding amine concentration, and the relation k''/k' is equal to k_3^{Am}/k_2 (eq 2). When k_{obs} is divided by the appropriate amine concentration, the second-order rate coefficient k_A can be calculated. Although the data of this type of reaction are usually analyzed by eq 2, we have found that eq 4 is much more sensitive, particularly for the calculation of the k''/k' ratio.[10,14] Hence, the rate

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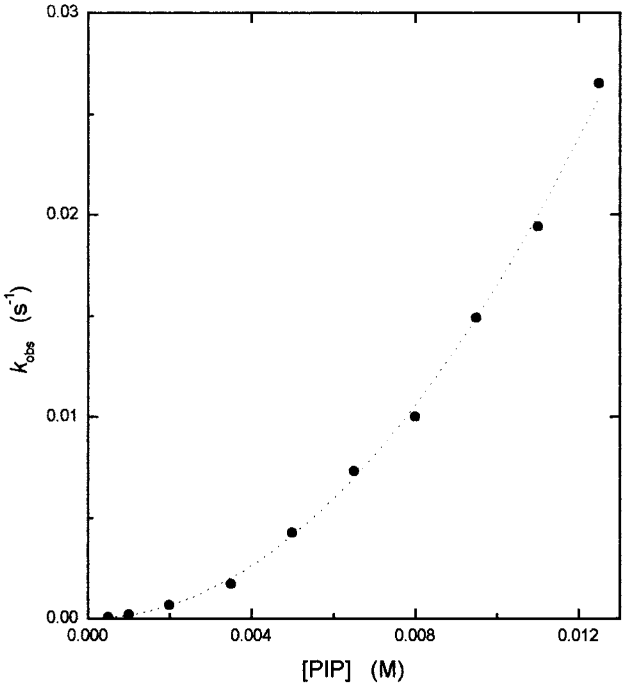

Figure 1. Dependence of the pseudo-first-order rate constant (k_{obs}) on the PIP concentration, for the reaction between FDNB and PIP in *n*-hexane. [FDNB] = 5.4×10^{-5} M. The dotted line shows the fitting by eq 4.

Table 1. Rate Constants for the Reaction of FDNB with nBA in *n*-Hexane[a]

10^3[nBA] (M)	0.33	0.99	3.02	6.80	7.80	11.0	21.0	52.0
10^3k_{obs} (s^{-1})[b]	0.007	0.037	0.158	0.413	0.728	1.02	2.84	19.6

[a] [FDNB] = 5.4×10^{-5} M. [b] r >0.999.

Table 2. Rate Constant for the Reaction of FDNB with nBA and PIP in *n*-Hexane Calculated by Fitting Equation 4

amine	k' (s^{-1} M^{-1})[a]	k'' (s^{-1} M^{-2})[a]	k''/k' (M^{-1})	n[b]
nBA	0	7.2 ± 0.2	$\propto$	8
PIP	0	171 ± 5	$\propto$	10

[a] Parameter values calculated using 0.995 confidence level in nonlinear regression. [b] n: number of points.

coefficients were obtained by fitting the experimental k_{obs} values using eq 4.[14] The results are given in Table 2.

It should be noted that for the reactions between other nitro-activated substrates with aliphatic amines in *n*-hexane, we have proposed the formation of an electron-donor−acceptor complex (EDA) between the reactants prior to the formation of the Z intermediate.[10,14] A similar proposal has been made for the reaction of FNDB and amines in other nonpolar aprotic solvents.[21,22] Although we believe the complexes may also be formed in *n*-hexane, we have not made any attempt to measure these associations since the role of the EDA complex is not kinetically distinguishable under the conditions that the reactions have been studied.

As can be observed in Table 2, the uncatalyzed step (k') is not detected. According to Bunnett and Garst[23] when the values of k''/k' are small (<5) and the accelerating effects of the bases bear no relationship to their base strength, the reactions are not base catalyzed. On the other hand, high values (>50) indicate genuine base catalysis. Therefore, these reactions are considered to be genuinely base catalyzed in *n*-hexane. Similar base catalysis behavior was observed for these S$_N$Ar reactions in benzene,[17] toluene,[21] and cyclohexane.[22]

When the fluoride ion is the leaving group in a nonpolar solvent, the ratio k_3^{B}/k_2 may be so large as to make the k_2 term undetectable.[17] The results are consistent with what is expected[15,17] for a fluorine leaving group and the highly nonpolar character of this solvent ($\pi^*_{n-\text{hexane}} = -0.08$).[24] Though the fluoride ion is not a particularly poor leaving group in protic solvents, it becomes so in nonpolar aprotic solvents due to the high demand for solvation of the fluoride ion or the assistance to proton abstraction, which cannot be provided by the solvent. In the mechanism of catalysis proposed in this type of media[10,25] the decomposition of the Z intermediate proceeds via a cyclic transition state where a second molecule of amine acts as a bifunctional catalyst within aggregates of conveniently charged dipolar species.

The values of k'' ($=k_1k_3^{B_i}/k_{-1}$) for these reactions are very similar to the reported values in cyclohexane.[22] These values are over 3 orders of magnitude greater than the ones with 1-chloro-2,4-dinitrobenzene in the same[14] or a similar solvent.[22] This shows that even in base-catalyzed reactions, at least for these nonionic nucleophiles, fluorine appears as better nucleofuge than chlorine, probably because of its effect in reducing k_{-1}.[17] The fact that fluorine is a better leaving group than chlorine although a very well-known experimental fact still does not have a satisfactory explanation.[22]

When the reactivity of the amines is compared (Table 2), a value of $k''_{PIP}/k''_{nBA} \cong 23$ is obtained. Thus, for the reaction between FDNB and amines in *n*-hexane as well as in benzene[26] and cyclohexane[22] it seems that secondary amines are more prone to base catalysis than a primary aliphatic amine of comparable basicity. In addition, PIP is a better catalyst than nBA.

Reaction in AOT/*n*-Hexane/Water Microemulsion. Influences of several variables were investigated while we tried to elucidate the mechanism of these reactions in AOT/*n*-hexane/water reverse micelles.

Effects of AOT Concentration. The kinetics of these reactions was studied at different AOT concentrations, keeping the other experimental conditions fixed. Typical results are shown in Figure 2 and Table 3. As can be observed, k_{obs} increases with increasing AOT concentration until approximatelly 0.1 M, and the plots show a downward curvature. At higher AOT concentrations ([AOT] > 0.1 M), the reaction rates change very little. The behavior is observed for both nucleophiles at $W_0 = 0$ and 10.

The initial increase on k_{obs} values with the increase of surfactant concentration could be due to the gradual incorporation of the reactants into the micellar aggregates. However, at [AOT] greater than 0.1 M saturation in the micellar interface is reached and no further micellar catalysis is observed. When taking into account that at $W_0 \leq 10$, two pseudophases are mainly present, it can be assumed that the reaction is limited to the

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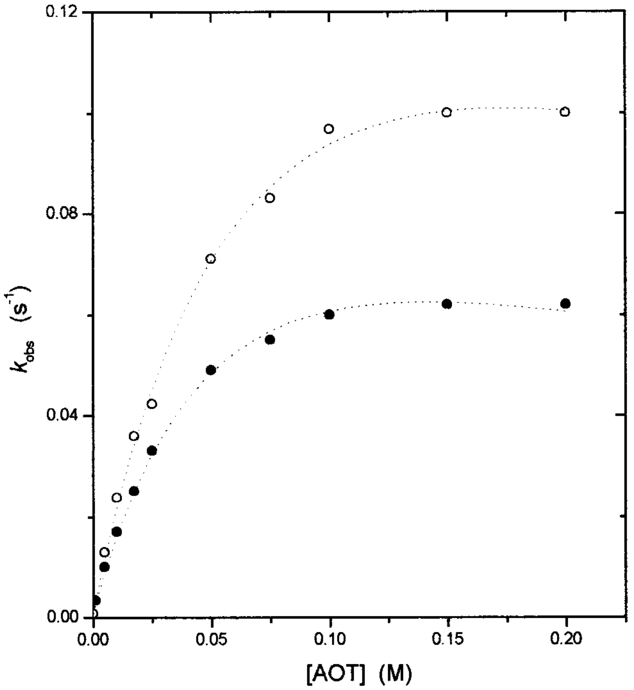


Figure 2. Dependence of the pseudo-first-order rate constant (k_{obs}) on the AOT concentration, for the reaction between FDNB and nBA in AOT/*n*-hexane/water reverse micelles: (○) $W_0 = 0$; (●) $W_0 = 10$. [FDNB] = 4.2×10^{-5} M, [nBA] = 1.0×10^{-2} M. The dotted lines show the fitting by eq 11.

Table 3. Rate Constants for the Reaction of FDNB with PIP in AOT/*n*-Hexane/Water Reverse Micelles, at Different AOT Concentrations

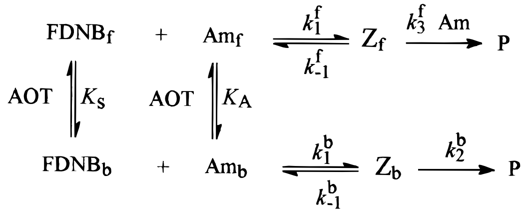
$W_0 = 0^a$		$W_0 = 10^b$	
[AOT] (M)	10^3k_{obs} (s^{-1})	[AOT] (M)	10^2k_{obs} (s^{-1})
0	4.5	0	3.5
0.0049	9.0	0.001	6.0
0.0099	11.1	0.005	18.0
0.025	17.5	0.010	25.0
0.048	23.9	0.0175	34.0
0.075	31.0	0.025	49.0
0.10	34.0	0.050	72.0
0.15	36.0	0.075	82.0
0.20	37.0	0.10	88.0
		0.15	92.0
		0.20	92.0

[a] [FDNB] = 5.2×10^{-5} M, [PIP] = 5×10^{-3} M. [b] [FDNB] = 1.0×10^{-4} M, [PIP] = 1.5×10^{-2} M, $r > 0.999$.

n-hexane phase and the micellar interface.[2] Considering that the observed rate constants for these reactions in the reverse micelles are several orders of magnitude faster than in pure *n*-hexane, it is inferred that in the micelles the reactions effectively take place mainly at the interface of the aggregates.

Since both reactants may be distributed between the two environments, the interface and the bulk organic solvent, in principle, a mechanism summarized by Scheme 1 can be proposed, where subscripts f and b indicate the organic phase and in the micellar pseudophase, respectively, AOT represents the micellized surfactant molecules, and Am is the amine nucleophile. The rate coefficients of the reaction (k_1, k_{-1}, k_2, and k_3) were defined above. K_s and K_A are the distribution constants between the organic phase and micellar pseudophase of the substrate FDNB and amines, respectively.

Scheme 1



For the reaction in the micelle interface the formation of the intermediate Z_b is assumed to be rate limiting. As discussed before, these reactions in the organic phase, *n*-hexane, are wholly base catalyzed and the decomposition of the intermediate Z_b is rate limiting for both nucleophiles. However, these S_NAr reactions are not base catalyzed in polar solvents.[17] The micropolarity of the interface in reversed micelles of AOT/*n*-hexane/water is always higher than in *n*-hexane.[27] Thus, it can be assumed that the reactions of FDNB with nBA and PIP are not base catalyzed in the micellar interface, as confirmed in the study of the effects of the amine concentration, shown in the next section.

The rate of the reaction can be expressed by eq 5, where k_f represents the intrinsic second-order rate constant in the organic solvent ($k_f = k''[Am_f]$). For absolute

$$\frac{d[P]}{dt} = k_f[Am_f][FDNB_f] + k'_b\frac{[Am_b][FDNB_b]}{\bar{v}[AOT]} \tag{5}$$

comparison of reactivities in different media, the molar reaction volume at the interface, $\bar{v}$, should be known. This can be estimated from the molar volume of AOT in the reverse micelles, which can be taken as $\bar{v}$.[29] Thus, k'_b is the conventional intrinsic second-order rate constant in the interface. The concentrations in square brackets refer to the total volume of reverse micelle.

The distribution constant of FDNB is given by eq 6.

$$K_s = \frac{[FDNB_b]}{[FDNB_f][AOT]} \tag{6}$$

A simple mass balance using the distribution constant K_s and the analytical concentration of FDNB, $[FNDB_T]$, allows us to calculate the $[FDNB_b]$ (eq 7). In the same

$$[FDNB_b] = \frac{K_s[AOT][FDNB_T]}{1 + K_s[AOT]} \tag{7}$$

way, using the distribution constant defined by eq 8 for the nucleophiles, $[Am_b]$ can be expressed by eq 9. If $[Am_T] \gg [FDNB_T]$, a pseudo-first-order behavior for the kinetics

$$K_A = \frac{[Am_b]}{[Am_f][AOT]} \tag{8}$$

$$[Am_b] = \frac{K_A[AOT][Am_T]}{1 + K_A[AOT]} \tag{9}$$

of the reaction is assumed. Then, by replacing $[FDNB_b]$ and $[Am_b]$ in eq 5, we can obtain the final expression for the rate (eq 10) and the observed pseudo-first-order rate

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Table 4. Rate Constant for the Reaction of FDNB with nBA and PIP in Different Media

amine	medium	k'_b (s^{-1} M^{-1})	K_A (M^{-1})	n
nBA	AOT/*n*-hexane ($W_0 = 0$)	2.83 ± 0.16^a	3.9 ± 0.3	10
		2.59 ± 0.10^b		7
	AOT/*n*-hexane ($W_0 = 10$)	1.34 ± 0.21^a	6.2 ± 0.3	11
		1.08 ± 0.10^b		7
PIP	AOT/*n*-hexane ($W_0 = 0$)	2.42 ± 0.23^a	2.9 ± 0.2	9
		2.95 ± 0.10^b		10
	AOT/*n*-hexane ($W_0 = 10$)	14.3 ± 0.6^a	5.4 ± 0.3	11
		15.2 ± 0.2^b		9

[a] From fitting of plot k_{obs} vs [AOT] by eq 11. [b] From fitting of the plot k_{obs} vs [Am] by eq 11; parameter values calculated using the 0.995 confidence level in nonlinear regression. *n*: number of points.

constant k_{obs} (eq 11), where k'_b represents the second-order rate constant for the bimolecular interfacial reaction.

$$\frac{d[P]}{dt} = k_{obs}[FDNB_T] \qquad (10)$$

$$k_{obs} = \frac{k_f + (k'_b K_s K_A [Am_T][AOT]/\bar{v})}{(1 + K_s[AOT])(1 + K_A[AOT])} \qquad (11)$$

The variation of k_{obs} with the AOT concentration can now be explained from eq 11. This equation shows that when the values of products between the distribution constants and [AOT] are not negligible with respect to unity, k_{obs} would exhibit a nonlinear relationship with the surfactant concentration.

The intrinsic second-order rate constant of the reaction in the organic solvent, k_f, is known from the studies of these reactions in *n*-hexane (Table 2). The molar volume of AOT, to be taken as $\bar{v}$, was estimated in a value of 0.38 M^{-1}.[28,29]

The distribution constant, K_s, was assumed the same as that for FDNB in AOT/*n*-heptane/water obtained by using a fluorescence quenching method.[20] K_s is 8.0 ± 1.5 M^{-1} and independent of W_0. Thus, the substrate is only partitioned between the micellar interface and the organic solvent and completely excluded from the water pool. The values of K_A and k_b were estimated by fitting the experimental data of k_{obs} vs [AOT] with eq 11. Nonlinear least-squares curve fitting was used to generate a fit curve in the graph. Typical fits are shown in Figure 2 (dotted line) for the reaction of FDNB with nBA at different AOT concentrations. Similar fittings were obtained for the reaction with PIP. The results for the k'_b and K_A at different values of W_0 are shown in Table 4.

The partition constants for the amines are similar to those obtained by Leis et al.[29] for different kinetic reactions. To compare, we have also determined the partition coefficients K_{oil}^{water} defined by the ratio between the mole fraction of amines in water and *n*-hexane. The K_{oil}^{water} values are 0.3 and 0.5 for PIP and nBA at 25 °C, respectively. A similar value was reported for PIP,[28] and they are smaller than the values of K_A. However, K_{oil}^{water} values measured in a macroscopic two-phase system, are not a good approximation for the corresponding partition constant in the micelle due to the differences between the physicochemical properties of bulk water and water trapped in the microdroplet. The ionic strength in the aqueous core of the microemulsion can be 3−5 M,[29] so K_{oil}^{water} should be lower in the microemulsion consistent with the low affinity of the amines for the water pool. The values of K_A obtained by kinetic measurement may indeed be reflecting a more real and different microscopic situation. In fact, aliphatic amines are good hydrogen bond donors and the AOT polar head of reverse micelles in *n*-hexane has been shown to be a very good hydrogen bond acceptor.[30,31] Thus, the values of K_A seem to be quite justifiable, the amines, such as nBA and PIP, being able to reach the micelle interface through hydrogen bond interactions with the AOT.

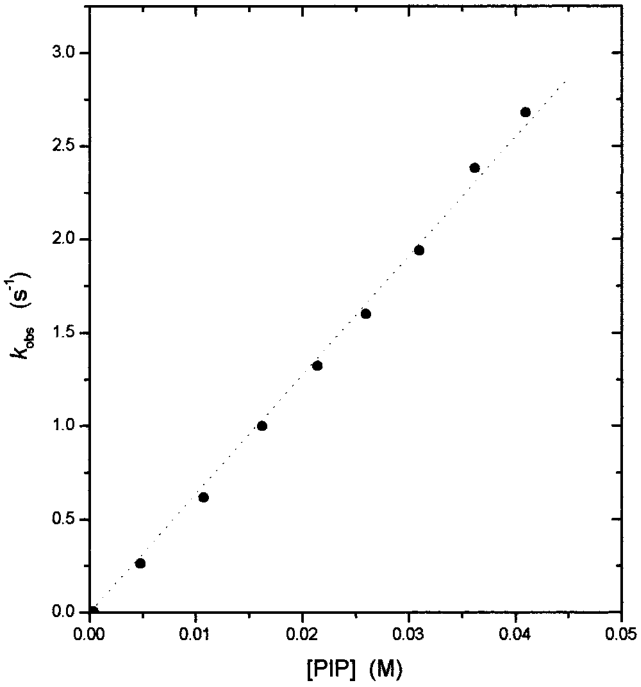

Figure 3. Variation of the pseudo-first-order rate constant (k_{obs}) with the PIP concentration, for the reaction between FDNB and PIP in AOT/*n*-hexane/water reverse micelles. $W_0 = 10$, [FDNB] = 1.0×10^{-4} M, [AOT] = 0.2 M. The dotted line shows the fitting by eq 11.

Effect of Amine Concentration. To study the effect of amine concentration, the reactions were carried out at 0.2 M AOT at $W_0 = 0$ and 10. The AOT concentration chosen allows us to obtain the rates, which correspond to the value in the plateau of the plots of k_{obs} vs [AOT]. Typical results are shown in Figure 3 and Table 5.

In all cases, the experimental data show linear relationships of k_{obs} with the nucleophile concentration, indicating a first-order behavior in relation to the nucleophile. These results imply that the reaction is occurring in the micelle interface and is not base catalyzed, as previously proposed in Scheme 1.

By introduction of the proper values of K_A obtained in the experiments with variation [AOT], the values of k'_b were recalculated for each nucleophile at $W_0 = 0$ and 10 by fitting the new set of experimental data (Figure 3 and Table 5) by eq 11. The results are compared in Table 4. As can be seen, good estimates for k'_b within experimental error are obtained by two independent methods.

Thus, the kinetic results are consistent with the assumption that in AOT/*n*-hexane/water reverse micelles these reactions are not base catalyzed ($k_A = k'_b = k_1$) and

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Table 5. Rate Constants for the Reaction of FDNB with nBA and PIP, in AOT/*n*-Hexane/Water Reverse Micelles, at Different Amine Concentrations[a]

nBA, $W_0 = 0$		nBA, $W_0 = 10$		PIP, $W_0 = 0$	
10^2[nBA] (M)	10^2k_{obs} (s^{-1})	10^2[nBA] (M)	10^2k_{obs} (s^{-1})	10^3[PIP] (M)	10^2k_{obs} (s^{-1})
0.5	4.6	0.65	3.1	0.50	0.4
0.65	5.9	0.80	3.9	1.16	0.8
0.8	7.4	0.93	4.5	1.97	1.5
0.95	8.8	1.00	4.9	3.44	2.7
1.10	10.0	1.10	5.3	4.85	3.9
1.20	11.0	1.25	6.0	6.50	5.3
1.35	12.0	1.35	6.5	8.00	6.6
				9.50	8.0
				11.10	9.7
				12.70	11.0

[a] [AOT] = 0.2 M, [FDNB] = 4.2×10^{-5} M, $r > 0.999$.

the formation of Z intermediate is rate determining. Hence, it can be concluded that the reactions take place mainly in the interface, which is more polar, as opposed to the organic medium. Moreover, the polar heads of the surfactant with strong hydrogen bond acceptor ability in this micellar system[30] could be assisting the intermediate decomposition to products.

When the amine reactivity is compared, both nucleophiles show similar rate constants at $W_0 = 0$ but these are about 10-fold higher for PIP at $W_0 = 10$ (Table 4). It is known that for S_NAr reactions in which the formation of the intermediate Z is rate determining, nBA is usually 1 order of magnitude less reactive than PIP.[32,33] The superior reactivity of secondary over primary amines has been adduced to be due to a favorable ion-induced dipole interaction in the transition state between the partially positively charged amine nitrogen and the polarizable alkyl moieties attached to it.[33] The differences in nucleophilicity seem to be particularly noticeable at $W_0 = 10$, where hydration diminishes the reactivity of the amines as shown below.

Effect of Amount of Water Dispersed. The effects of changing the value of W_0 on k_{obs} for both amines are shown in Figure 4. As can be observed in Figure 4a, for the reaction of FDNB with PIP, k_{obs} increases while W_0 increases up to $W_0 \cong 10$, above this value ($W_0 > 10$) k_{obs} decreases. Under these experimental conditions, as was discussed before, $k_A = k_1$. Analyses of the solvent effect on k_1 for similar reactions using polarity parameters showed that k_1 increases from less polar to more polar solvents.[13] On the other hand, experimental evidence shows that the dielectric constant of the interface of small droplets ($W_0 < 10$) gradually increases with W_0.[34] It has also been demonstrated with a betaine dye that the micropolarity at the interface increases, reaching at $W_0 = 10$ a polarity similar to that of glycerol ($E_T^{30} = 62.72$ kcal/mol).[27] Thus, the increase in the value of k_{obs} could be explained by considering the increases in the polarity interface; consequently, stabilization of the Z intermediate is achieved and k_1 increases. For $W_0 > 10$, the water added is not required for hydration of surfactant heads or counterions but makes up a core with properties similar to those of bulk water.[35] In these conditions, hydration of the amine can occur and the amine reactivity decreases because its nucleophilicity diminishes.

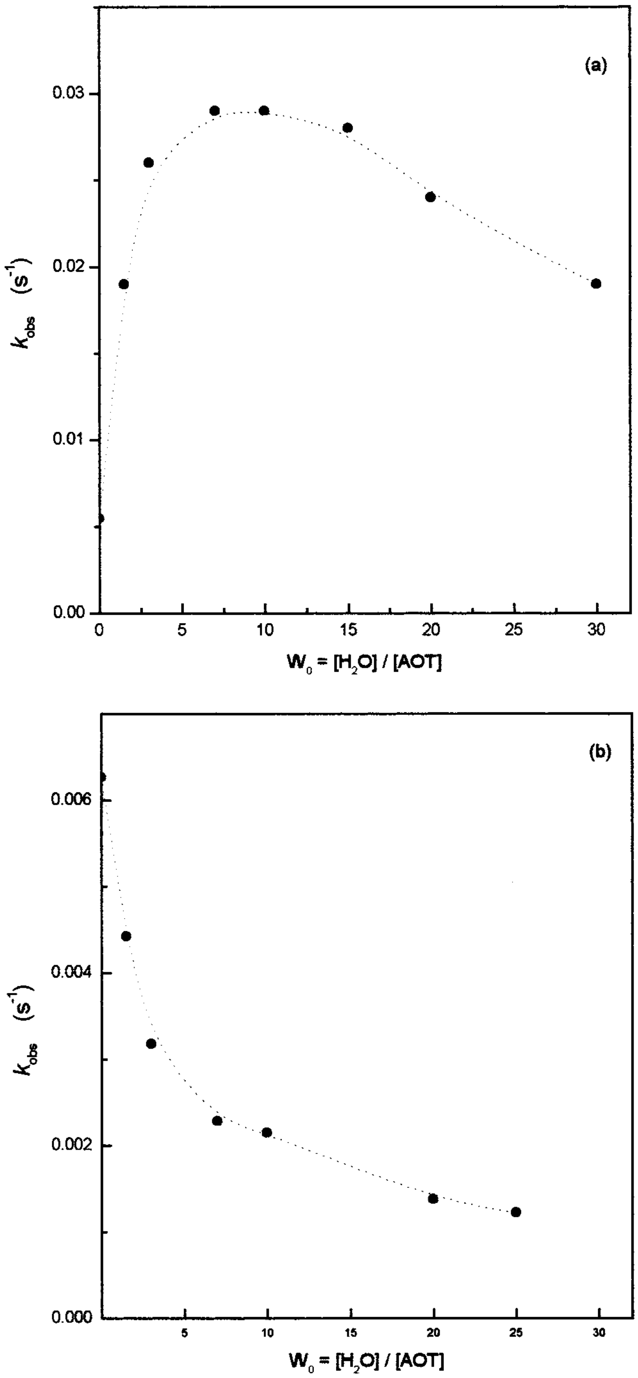

Figure 4. Variation of pseudo-first-order rate constant (k_{obs}) with W_0 in AOT/*n*-hexane/water reverse micelles, for the reaction of FDNB with (a) PIP ([FDNB] = 1.4×10^{-5} M, [PIP] = 1.5×10^{-3} M, [AOT] = 0.2 M) and (b) nBA ([FDNB] = 4.2×10^{-5} M, [nBA] = 1.0×10^{-3} M, [AOT] = 0.2 M).

A different situation is observed for the reaction between FDNB and nBA: the value of k_{obs} always decreases with W_0, as shown in Figure 4b. It is known, for S_NAr reactions of amines with a substrate that contains an *o*-nitro group, that intramolecular hydrogen bonding between the amino hydrogen atoms and the *o*-nitro group in the Z intermediate can occur in the so-

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called “built solvation”.[26,36] Since secondary amines have only one hydrogen atom on the N amine, this is involved in built solvation. However, primary amines have an extra hydrogen so the transition state for FDNB with nBA should be a good hydrogen-bond donor, which can be solvated by the polar heads of the AOT. Indeed, we have reported that strong hydrogen bond interactions between nitro-substituted aniline derivatives and the polar head of AOT molecules can be formed in the interface of this type of micelle.[30,31] When water is added, although there is an increase in polarity at the interface, competition between the NH group of the intermediate and water for the AOT headgroups can take place with a neat effect of lowering the rate constant. When the amount of water fulfills the hydration requirements of the surfactant ($W_0 \cong 10$), the same effects are observed for both amines.

Conclusions

The overall rates of the reaction of FDNB with nBA and PIP are accelerated at least 2 orders of magnitude in the reverse micelle medium with respect to the pure solvent. The initial steep increase with AOT concentration levels off at $\cong$ 0.1 M. These results suggest that the reactions in the system AOT/*n*-hexane/water occur in the micelle interface. A change in mechanism for the S_NAr reaction is observed. These reactions, which are wholly base catalyzed in *n*-hexane, in the reverse micelles are not. The formation of the Z intermediate is rate determining for both amines, due to the higher polarity in the micelle interface as compared with the bulk solvent. In addition, Z decomposition may be assisted by the polar heads of the surfactant in the polar interface. The kinetic behavior can be quantitatively explained taking into account the distribution of the substrate and amines. The results were used to evaluate the amine distribution constant between the micellar pseudophase and organic solvent and the intrinsic second-order rate coefficient of the S_NAr reaction in the interface. The rates depend on the amine and water content. At the same value of W_0, PIP reacts faster than nBA, as normally observed in these type of reactions. However, the observed rates always diminish for the primary amine as W_0 increases while for PIP they first increase until $W_0 = 10$ and decrease afterward. These facts are explained by considering the difference in hydrogen bond donor ability of the Z intermediates competing with hydration of the polar heads of the surfactant.

The results in this study can be used as a good model to predict micellar catalysis for reaction between nonionic substrates that give a zwitterionic type and hydrogen bond donor intermediate.

Experimental Section

General Information. UV−visible spectra were recorded on a Hewlett-Packard HP 8452 spectrophotometer or Hi-Tech Scientific Stopped-Flow SHU SF-51 (SU-40 spectrophotometer Unit) for very fast reactions. The HPLC measurements were performed on a Varian 5000 liquid chromatograph equipped with a UV−visible variable λ detector (Varian 2550) operating at 250 nm with a Varian MicroPak SI-5 (150 mm × 4 mm i.d.) column and 1% 2-propanol in *n*-hexane as solvent.

Materials. 1-Fluoro-2,4-dinitrobenzene (FDNB) from Aldrich, *n*-butylamine, and piperidine from Riedel-deHaën were used without further purification. Sodium bis(2-ethylhexyl) sulfosuccinate (AOT) from Sigma purified by the procedure described in ref 37. was dried under vacuum over P_2O_5. *n*-Hexane (Sintorgan, HPLC quality) was used as received. Water was first distilled over potassium permangamate and then bidistilled until a conductivity of 0.3−0.5 $\mu\Omega^{-1}$ M^{-1} at 298 K was reached.

Procedures. Stock solutions of AOT reverse micelles were prepared by weighing and dilution in *n*-hexane. A stock solution of 1 M AOT was agitated in a sonicating bath until the reverse micelle was optically clear. The appropriate amount of stock solution to obtain a given concentration of AOT in the micellar media was transferred into the cell. The addition of water to the corresponding solution was performed using a calibrated microsyringe. The amount of water present in the system was expressed as the molar ratio between water and the surfactant present in the reverse micelle ($W_0 = [H_2O]/[AOT]$). The lowest value of W_0 called $W_0 = 0$ corresponds to a system with no addition of water, and its presence corresponds to the intrinsic humidity of the system ($W_0 \cong 0.3$).

The partition coefficient for the distribution of the amines between pure water and *n*-hexane (K_{oil}^{water}) were measured as follows. A solution of amines with measured quantities of the solvent were left to equilibrate with known volumes of water by continuous stirring for 1 day at 25 °C. The concentration of amine in the aqueous phase was determined by titration against hydrochloric acid, with a phenolphthalein as indicator.[29]

Kinetics. Reactions were followed spectrophotometrically by the increase in the maximum absorption band of the product, *N*-alkyl-2,4-dinitroaniline, at 25.0 ± 0.5 °C. To start a kinetic run, a stock solution of FDNB was added (10 μL) into a thermostated cell containing the reverse micelle solution. The FDNB concentration was $(1-0.5) \times 10^{-4}$ M. The kinetic runs were performed by following the increase in the absorbance of the product of the reaction. When the reaction was very fast, a stopped flow equipment set at the λ_{max} of the product was used. In all the cases, pseudo-first-order plots were obtained in an excess of nucleophile. The pseudo-first-order rate constants (k_{obs}) were obtained by a nonlinear least-squares fit of the experimental data absorbance vs time ($r > 0.999$) by first-order rate equation. The value of the absorbance at infinite reaction time was consistent with the value obtained from authentic samples of the reaction product, within 3%. The pooled standard deviation of the kinetic data, using different prepared samples, was less than 5%.

Acknowledgment. We gratefully acknowledge the financial support for this work by the Consejo Nacional de Investigaciones Científicas (CONICET), Consejo de Investigaciones Científicas y Tecnológicas de la Provincia de Córdoba (CONICOR) and Secretaría de Ciencia y Técnica de la Universidad Nacional de Río Cuarto. N.M.C. thanks CONICET for a research fellowship.

JO9818632

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