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Catalysis of α-naphthyl acetate hydrolysis by *o*-iodosobenzoic acid in micellar solutions of cetyltrimethylammonium bromide

Dale Eric Wurster and Jatin M. Patel

College of Pharmacy, University of Iowa, Iowa City, IA 52242 (U.S.A.)

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Summary

Hydrolysis of α-naphthyl acetate proceeds at a very slow rate in solutions near neutral pH. This reaction was found to be accelerated when carried out in surfactant solutions of cetyltrimethylammonium bromide which also contained *o*-iodosobenzoic acid, a strong nucleophile. The reaction followed pseudo-first-order kinetics and the rate constant versus surfactant concentration profile exhibited the maximum typical of bimolecular reactions conducted in micellar solutions. The calculated entropy of activation for the reaction supported a bimolecular mechanism of hydrolysis. The binding constant of α-naphthyl acetate for the micelle and the rate constant in the micellar pseudophase were determined from kinetic data using the pseudophase model. The influences of added salt concentration, solution pH and nucleophile concentration were evaluated.

Introduction

α-Naphthyl acetate has a carbonyl group which is susceptible to nucleophilic attack. At pH 7.5, the hydrolysis of α-naphthyl acetate proceeds at a very slow rate. However, when the same reaction is conducted in a micellar solution of cetyltrimethylammonium bromide (CTAB, pH 7.5) which also contains *o*-iodosobenzoic acid (IBA), a strong nucleophile, appreciable acceleration of the reaction rate is observed. Importantly, there is minimal reaction rate acceleration in the absence of either the CTAB or the IBA. IBA has previously been found to catalyze the hydrolysis of some phosphates and esters in micellar solution (Moss et al., 1983, 1984; Katritzky et al., 1988; Hammond et al., 1989; Leslie, 1989). In some of these cases (Moss et al., 1983, 1984), it has been demonstrated that IBA behaves like a 'true' catalyst and that there is complete regeneration of IBA in the reaction. Since this system is of potential use in the detoxification of many hazardous substances, further study of the behavior of IBA in micellar systems is warranted.

The reaction rate acceleration of bimolecular reactions in micellar solutions has generally been attributed to the partitioning of substrates into the micellar pseudophase, which results in higher

Correspondence: D.E. Wurster, College of Pharmacy, University of Iowa, Iowa City, IA 52242, U.S.A.

localized concentrations of the two substrates (Berezin et al., 1973; Yatsimirski et al., 1974). It is also possible that rate acceleration is due to a more favorable reaction environment (Berezin et al., 1973). In the case of IBA, it was not known which phenomenon predominated. It was also desired to determine the magnitude of the partitioning of the substrates into the micellar pseudophase, the turnover (regeneration) behavior of IBA, and the second-order rate constant for attack of the ester by ionized IBA in the micellar phase. The latter was accomplished by studying the effect of pH on the reaction to determine the pK_a of IBA in the micellar system.

Materials and Methods

Test solutions

Solutions of CTAB (0–11 mM, Sigma Chemical Co., St. Louis, MO) were prepared in pH 7.5 buffer solutions made up of sodium phosphate (monobasic) and potassium phosphate (dibasic) (both obtained from Fisher Scientific, Fair Lawn, NJ). Ionic strength was adjusted to 0.30 M with potassium chloride (Fisher Scientific, Fair Lawn, NJ). Appropriate amounts of IBA (Sigma Chemical Co., St. Louis, MO) were added to these solutions to obtain the required concentrations. The solutions were placed in 100 ml volumetric flasks. These flasks were then kept in a circulating water bath maintained at 30 °C. For those studies designed to test the effect of ionic strength on the rate of hydrolysis of α-naphthyl acetate (Sigma Chemical Co., St. Louis, MO), surfactant solutions (3 mM) were prepared with various total ionic strengths. Ionic strength was adjusted using potassium chloride.

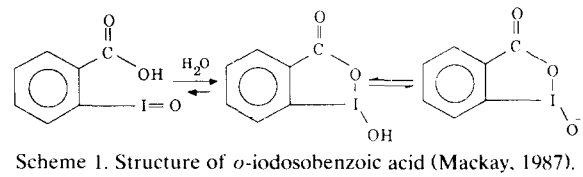
Kinetic studies

α-Naphthyl acetate was dissolved in ethanol and added to volumetric flasks containing CTAB solutions maintained at 30 °C. Sufficient α-naphthyl acetate stock solution was added that the initial concentration in the micellar solution was 2.0×10^{-4} M. The concentration of ethanol in the final solution was never greater than 0.5% v/v. Samples withdrawn during a kinetic run were diluted with a pH 5.0 acetate buffer solution (sodium acetate, Fisher Scientific, Fair Lawn, NJ and glacial acetic acid, American Scientific Products, McGaw Park, IL) to slow the reaction. These samples were then analyzed for α-naphthyl acetate and α-naphthol using a fluorimetric assay (Shimadzu RF-540 fluorimeter, Kyoto, Japan). The excitation and emission maxima used for α-naphthyl acetate were 260 and 333 nm, respectively, while the excitation and emission maxima for α-naphthol were 294 and 464 nm, respectively. The dilution process resulted in samples with CTAB concentrations that were lower than the CMC. Therefore, fluorescence quenching was not a problem. All α-naphthyl acetate reaction conditions were run in triplicate. The resultant data were analyzed to determine the pseudo-first-order rate constants. The reaction rate constant versus surfactant concentration profile was then analyzed according to the pseudophase model to determine the binding constants and the rate constant for ester hydrolysis in the micellar phase.

Results and Discussion

Reaction mechanism

The active form of IBA is the anion formed from 1-hydroxy-1,2-benziodoxol-3(1H)-one, the stable valence tautomer of IBA in aqueous solution (Scheme 1, Mackay, 1987). The proposed mechanism (Scheme 2) of α-naphthyl acetate hydrolysis involves the nucleophilic attack by the active anionic form of IBA on the carbonyl carbon to form an acylated intermediate and α-naphthol anion. The formation of the latter was verified using the fluorescence spectra of the reaction mixtures. The acylated intermediate is then rapidly hydrolyzed to form acetic acid and the original nucleophile.



Scheme 1. Structure of *o*-iodosobenzoic acid (Mackay, 1987).

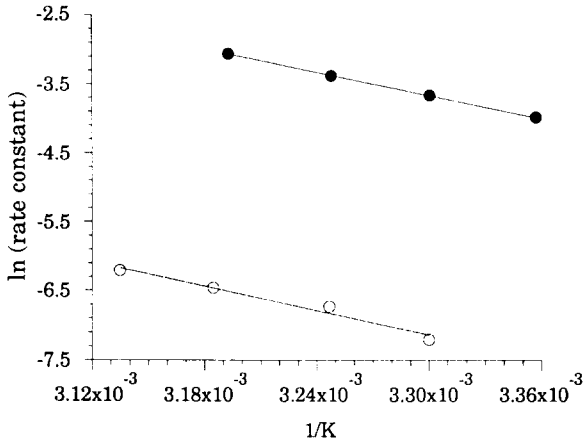


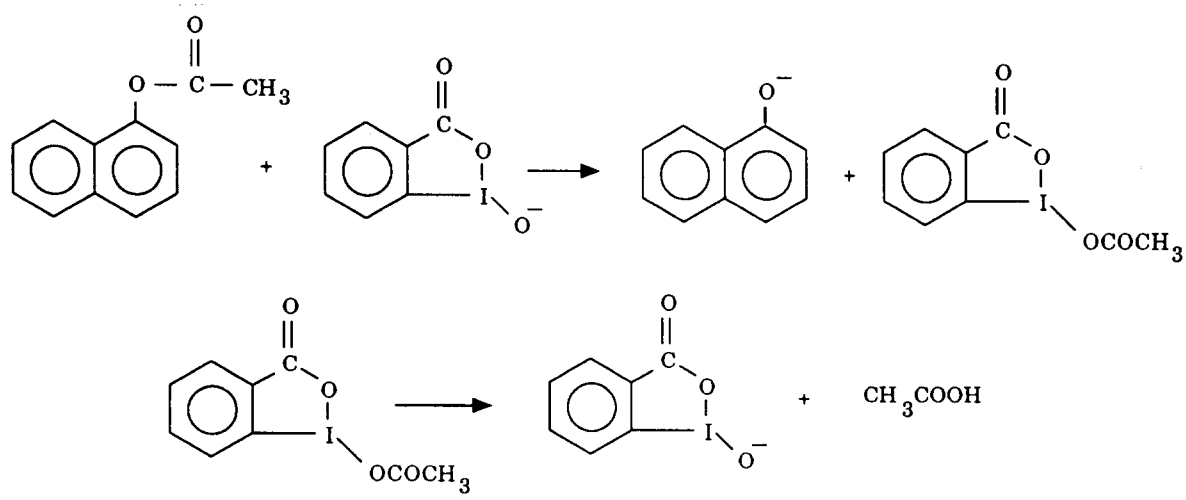
Fig. 1. Effect of temperature on the rate of α-naphthyl acetate hydrolysis at pH 7.5 in the absence of surfactant (○) and in the presence of 3 mM CTAB (●). IBA concentration was kept constant at 1.0×10^{-4} M and the ionic strength was maintained constant at 0.30 M. Initial α-naphthyl acetate concentration was 2.0×10^{-4} M.

A study of the temperature dependence of the reaction was performed to confirm that the reaction was bimolecular in nature (Fig. 1). The entropy of activation at 30 °C, calculated using Eqn 1 (Laidler, 1965):

$$k = e\frac{k_B T}{h}\exp^{\frac{\Delta S^{\dagger}}{R}}\exp^{-\frac{E_a}{RT}} \qquad (1)$$

was found to be -44.9 cal mol^{-1} K^{-1} in solutions without surfactant and -39.3 cal mol^{-1} K^{-1} in 3 mM CTAB solutions. In this equation, k_B is Boltzmann's constant, k represents the rate constant, h is Planck's constant and T denotes the temperature. $\Delta S^{\dagger}$, E_a and R have their customary meanings. The two activation entropies are essentially equal indicating that the reaction mechanism does not change in the micellar environment. The fact that the entropies of activation are negative instead of positive indicates that the reaction follows a bimolecular mechanism.

HPLC analysis of the reaction mixture as a function of time revealed a decrease in the concentration of IBA, which is apparently contrary to the 'true catalyst' behavior observed previously (Moss et al., 1983, 1984). A stability study of IBA in pH 7.5 phosphate buffer (no α-naphthyl acetate present, $T = 30$ °C) showed that less than 1% degraded in 2 days. Upon addition of α-naphthol to IBA, however, loss of IBA was detected after as little as 1 h, with about 63% degradation seen in 19 h. α-Naphthol concentration also decreased with time and there was a 1 : 1 stoichiometry for the disappearance of the two compounds (Fig. 2). Therefore, the disappearance of IBA is not due to incomplete regeneration during its reaction with α-naphthyl acetate, but rather is a result of its reaction with α-naphthol. This reaction explains the unexpected be-



Scheme 2. Proposed mechanism of α-naphthyl acetate hydrolysis by *o*-iodosobenzoic acid.

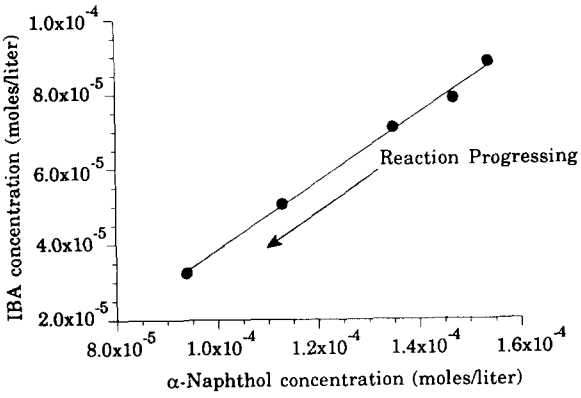


Fig. 2. Evidence for the 1:1 stoichiometry of the reaction between IBA and α-naphthol. Slope = 0.91, $r^2 = 0.996$.

havior seen for α-naphthyl acetate hydrolysis for low CTAB concentrations wherein α-naphthol appearance did not relate quantitatively to α-naphthyl acetate loss at all time intervals. It also explains the deviation from linearity of the first-order plots of α-naphthyl acetate degradation when the CTAB concentration was low. At worst, deviation from linearity was observed after 1.5 half-life periods. When the CTAB concentration was greater than 0.5 mM, however, the first-order plots were linear to greater than 2.5 half-life periods.

Pseudophase model

Unlike unimolecular reactions carried out in micellar solutions, the reaction rate constant versus surfactant concentration profiles for bimolecular reactions do not exhibit a steady increase of the reaction rate to a plateau. Instead, a maximum in the profile is observed. This maximum can be readily explained when the distribution of the two substrates involved in the reaction is considered. The initial increase in reaction rate is the result of increased amounts of the reactants in the micellar pseudophase. Once the maximum amounts of reactants in the micellar pseudophase are obtained, further addition of surfactant serves only to dilute the reactants. A lowering of the reaction rate constant is thus obtained. For bimolecular reactions, the observed reaction velocity, v, averaged over the whole volume of the system, can be expressed in terms of the reaction velocities in the micellar and aqueous phases (Berezin et al., 1973):

$$v = v_m CV + v_b(1 - CV) = k_{obs}[A]_0[B]_0 \qquad (2)$$

In Eqn 2 v_m and v_b are the reaction velocities in the micellar and bulk phases, $[A]_0$ and $[B]_0$ denote the initial concentrations of the two reactants, A and B, in the whole volume of the system, C is the surfactant concentration less the CMC, k_{obs} represents the experimental rate constant and V is the molar volume of the surfactant in the micellar state. If it is assumed that the law of mass action is satisfied, Eqns 3 and 4 can be obtained:

$$v_m = k_m[A]_m[B]_m \qquad (3)$$

$$v_b = k_o[A]_b[B]_b \qquad (4)$$

In Eqns 3 and 4, k_m and k_o are the rate constants in the micellar phase and the bulk aqueous phase, respectively. Eqns 5 and 6 give the relationship between the total concentration of each reactant and their actual concentrations in a particular phase (i.e., Eqns 5 and 6 can also be written for component B):

$$P_A = \frac{[A]_m}{[A]_b} \qquad (5)$$

$$[A]_o = [A]_m CV + [A]_b(1 - CV) \qquad (6)$$

where P is the partition coefficient. In doing this, it is assumed that the equilibrium distribution of the substrates between the two phases is not altered by the occurrence of the chemical reaction. This is most likely true, since there is very rapid exchange of substrates between the two phases (Berezin et al., 1973). Since the molar volume of the surfactant, as it exists in the micelle, is difficult to obtain (Berezin et al., 1973), a binding constant, K, is defined according to Eqn 7:

$$K = V(P - 1) \qquad (7)$$

From Eqns 2–7, Eqn 8 can be obtained:

$$k_{obs} = \frac{k_o(1 - CV) + k_m P_A P_B CV}{(1 + K_A C)(1 + K_B C)} \quad (8)$$

In the case of dilute surfactant solutions, in which the volume fraction of the micellar phase, CV, is small, Eqn 8 can be simplified to:

$$k_{obs} = \frac{k_o + k_m P_A P_B CV}{(1 + K_A C)(1 + K_B C)} \quad (9)$$

Berezin and co-workers (1973) have given a detailed analysis of the various conditions that can arise for bimolecular reactions. These authors discuss cases where both reactants are weakly bound to or repelled from the micelle, one reactant is strongly bound while the other is weakly repelled and the case of most importance in micellar catalysis wherein both of the reactants are strongly bound to the micelle. In this latter case, considerable acceleration of the reaction rate is possible even if the surfactant micelles have no specific influence on reaction velocity. This acceleration occurs because both reactants are greatly concentrated in the micelle. In order for this to occur, the partition coefficients would be expected to be much greater than 1 and Eqn 7 can be approximated by Eqn 10:

$$\frac{K}{V} = P \quad (10)$$

As a result, Eqn 9 can be written as:

$$k_{obs} = \frac{k_o + \bar{k}_m K_A K_B C}{(1 + K_A C)(1 + K_B C)} \quad (11)$$

where $\bar{k}_m$, the micellar rate constant averaged over the effective micellar volume, is given by:

$$\bar{k}_m = \frac{k_m}{V} \quad (12)$$

Micellar effects

The value of the CMC used in this work was experimentally determined at an ionic strength of 0.3 M and found to be 6.8×10^{-5} M (Patel and Wurster, 1991). This CMC value compares well with the CMC values for the same surfactant compiled by Mukerjee and Mysels (1971) at various ionic strengths.

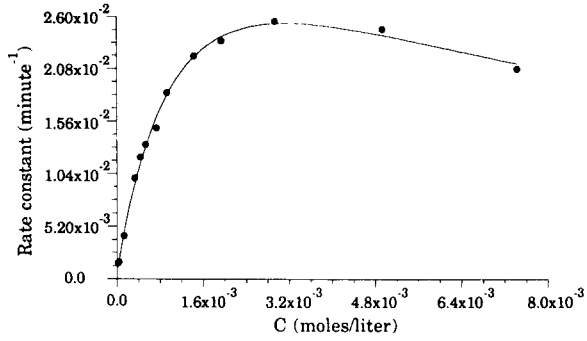


Fig. 3. Influence of CTAB concentration ($C = [CTAB] - [CTAB]_{cmc}$) on the rate of α-naphthyl acetate hydrolysis at pH 7.5 ($T = 30\,^{\circ}C$) in the presence of 1.0×10^{-4} M IBA. Ionic strength was equal to 0.30 M. Initial α-naphthyl acetate concentration was 2.0×10^{-4} M. The data were analyzed using nonlinear regression analysis and the pseudophase model. An r^2 value of 0.996 was obtained for the fit.

The rate of hydrolysis of α-naphthyl acetate increased appreciably in micellar solutions which had CTAB concentrations exceeding the experimentally determined CMC (Fig. 3). The enhanced reaction rate in micellar solutions of CTAB is most likely due to increased concentrations of α-naphthyl acetate and IBA in the micellar pseudophase. α-Naphthyl acetate should partition into the micelle because of its nonpolar nature. IBA, in its active form, is ionized (pK_a of 7.1, see below) and would be attracted to the multiplicity of positively charged head groups of the CTAB micelle. The partitioning of the reactants into the micelle results in their being in close proximity in a reduced volume, thereby providing a concentration advantage to the reaction. The reaction could also be catalyzed if the micellar pseudophase provided a chemical environment that facilitated the reaction to a greater extent than an aqueous medium. When Eqn 11 was used to analyze the rate constant vs surfactant concentration data, the value of the micellar rate constant, k_m (1.2×10^{-4} min^{-1}, 0.35 l/mol was used to estimate the molar volume of the

surfactant as it existed in the micelle) obtained from this analysis (Fig. 3) was lower than that observed for the reaction conducted in the absence of the surfactant (7.6×10^{-4} min^{-1}). This leads to the conclusion that the enhanced rate is due to the concentration of the substrates in the micellar pseudophase and not to enhanced reactivity in the micellar pseudophase. The lower value of the reaction rate constant in the micellar pseudophase, as compared to that in the aqueous phase, is not unusual (Leslie, 1989) and is usually attributed to the change in environment or orientation of substrates in the micellar phase. Arrhenius plots (Fig. 1) for the reaction revealed that the activation energy for the reaction was 11.5 kcal/mol when the reaction was carried out in a pH 7.5 buffer solution without any surfactant present. In a 3 mM solution of surfactant that had the same pH, the activation energy was 11.1 kcal/mol. These two activation energies are essentially equal, lending further support to the notion that the rate acceleration afforded by the micellar solutions is due to a concentration effect.

The binding constants obtained from the pseudophase model analysis of the rate constant vs surfactant concentration data (Eqn 11) were 434 l/mol for α-naphthyl acetate and 229 l/mol for IBA. Preliminary studies on the hydrolyses of several closely related naphthyl esters by IBA support the numerically higher binding constant as being for the ester since the value tentatively assigned to IBA remains relatively constant. This finding would be expected since the structure of the ester has more hydrophobic character than that of IBA.

To determine the second-order rate constant for attack of the ester by ionized IBA, α-naphthyl acetate hydrolysis was studied in 3 mM CTAB solutions, pH 7.5, at varying IBA concentrations. For this analysis, second-order rate constants were calculated by dividing the pseudo-first-order rate constants that were obtained experimentally by the analytical concentration of ionized IBA. The pK_a value of cyclized IBA was determined by studying the effect of pH on α-naphthyl acetate hydrolysis at a fixed surfactant concentration of 3 mM (Fig. 4). The pK_a value of 7.1 determined from this study compares well with the previously

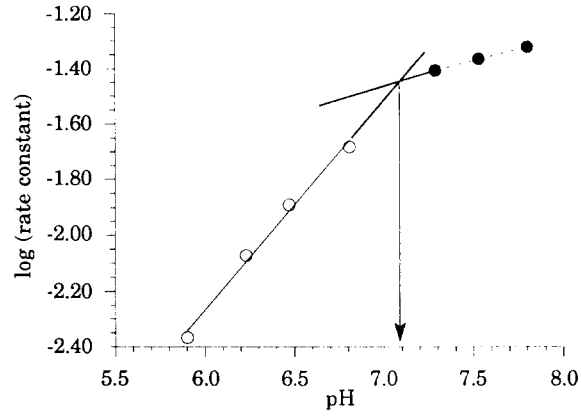


Fig. 4. Determination of the pK_a of IBA in a 3 mM CTAB system. α-Naphthyl acetate hydrolysis was studied as a function of solution pH at 30 °C. Initial α-naphthyl acetate concentration was 2.0×10^{-4} M.

reported values of 7.25 (Moss et al., 1983; kinetic study, surfactant present) and 7.02 (Mackay, 1987; titration study, presence of surfactant not specified). Using the pK_a value of 7.1, active nucleophile concentrations were calculated and used for the determination of the second-order rate constant for attack of ionized IBA on the ester. The slope of the plot in Fig. 5 gives the second-order rate constant for attack of ionized IBA on

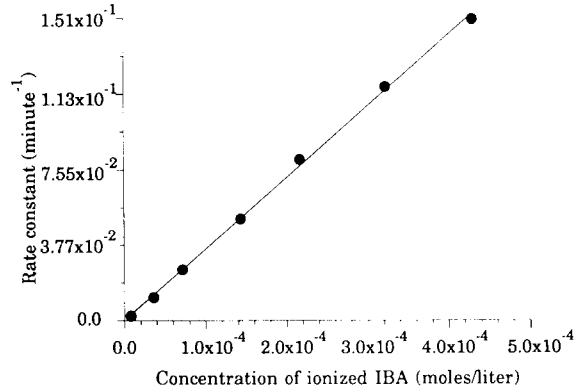


Fig. 5. Effect of ionized IBA on the rate of α-naphthyl acetate hydrolysis in a 3 mM CTAB solution (pH = 7.5, $T = 30$ °C, $\mu = 0.30$ M). The initial α-naphthyl acetate concentration was 2.0×10^{-4} M. The slope of the plot (357 M^{-1} min^{-1}) gave the second-order rate constant for attack of the ester by ionized IBA. The intercept and coefficient of determination (r^2) for the plot were 2.69×10^{-5} min^{-1} and 0.998, respectively.

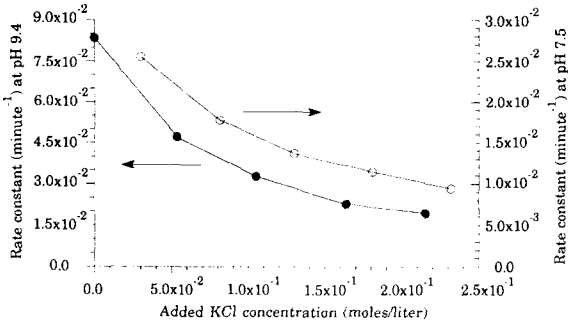


Fig. 6. Effect of potassium chloride addition on the rate of α-naphthyl acetate hydrolysis at pH 7.5 (○) and pH 9.4 (●). These studies were performed at 30 °C with an initial α-naphthyl acetate concentration of 2.0×10^{-4} M and an IBA concentration of 1.0×10^{-4} M.

the ester, which was found to be 357 l mol^{-1} min^{-1}.

Surprisingly, the pK_a value determined from titration studies in the absence of surfactant was also 7.1. Stabilization of the anionic form of IBA by the cationic micellar head groups would have been expected to have some effect on the pK_a. The lack of effect was confirmed by comparing the electrolyte effects observed for the reaction at pH 7.5 and 9.4 (Fig. 6). The overall rate constants are different at these two pH values since different hydroxide ion concentrations give different pseudo-first-order rate constants in the bulk phase. Since a positive micellar surface charge can stabilize the negatively charged dissociation product of a weak acid and since increasing the electrolyte concentration would decrease the positive surface charge of the micelle, it is possible that the decrease in rate constant at pH 7.5 upon electrolyte addition could be due to decreased ionization of IBA. However, at pH 9.4, where essentially all of the IBA would be ionized, a similar decrease in rate is still seen. This indicates that the decrease in the reaction rate constants with increasing electrolyte concentration is due to a decrease in solubilization of IBA and not due to decreased ionization of IBA.

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