Kinetics and Mechanism of Alkaline Hydrolysis of 4-Nitrophthalimide in the Absence and Presence of Cationic Micelles

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> ABSTRACT: Pseudo-first-order rate constants (k_{obs}) for alkaline hydrolysis of 4-nitrophthalimide (NPTH) decreased by nearly 8- and 6-fold with the increase in the total concentration of cetyltrimethyl-ammonium bromide ([CTABr]_T) from 0 to 0.02 M at 0.01 and 0.05 M NaOH, respectively. These observations are explained in terms of the pseudophase model and pseudophase ion-exchange model of micelle. The increase in the contents of CH₃CN from 1 to 70% v/v and CH₃OH from 0 to 80% v/v in mixed aqueous solvents decreases k_{obs} by nearly 12- and 11-fold, respectively. The values of k_{obs} increase by nearly 27% with the increase in the ionic strength from 0.03 to 3.0 M. The mechanism of alkaline hydrolysis of NPTH involves the reactions between HO⁻ and nonionized NPTH as well as between HO⁻ and ionized NPTH. The micellar inhibition of the rate of alkaline hydrolysis of NPTH is attributed to medium polarity effect. © 2001 John Wiley & Sons, Inc. Int J Chem Kinet 33: 407–414, 2001

INTRODUCTION

Phthalimide and its derivatives constitute an important class of organic compounds with numerous uses in biology and synthetic as well as polymer chemistry [1]. Micelles provide a microreaction medium that seems to be similar to one for many biological reactions [2,3]. The kinetics and mechanism of alkaline hydrolysis of phthalimide in the absence [4,5] and presence of micelles [6] have been studied in some detail. Cationic micelles inhibited the rate of alkaline hydrolysis of phthalimide [7], and the rate of this re-

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action was negligible in the cationic micellar pseudophase compared to that in aqueous pseudophase at $[NaOH] \le 0.05 \text{ M}$ [8]. Because of the insignificant rate of alkaline hydrolysis in cationic micellar pseudophase, the rate data were adequately explained in terms of the pseudophase model (PM) of micelle [9] rather than the pseudophase ion-exchange (PIE) model of micelle [10]. But the rate of hydrolysis of N-hydroxyphthalimide, within [NaOH] range of 0.006 to 0.018 M, was explained in terms of the PIE model [11]. The values of K_a of phthalimide and N-hydroxyphthalimide are 3×10^{-10} [12] and 1×10^{-6} M [13], respectively, and the rate of hydrolysis of phthalimide was found to be independent of [NaOH] within its range 0.005 - 0.050 M, while the rate of hydrolysis of N-hydroxyphthalimide was dependent upon [NaOH] at [HO⁻] ≥ 0.006 M.

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[⁻ OH]/M	$10^4 k_{\rm obs}/{\rm s}^{-1}$	$10^4 k_{\rm calcd}^{\rm b}/{\rm s}^{-1}$	$10^4 k_{\rm calcd}^{\rm c}/{\rm s}^{-2}$
$1.7 imes 10^{-5}$ d	13.0 ± 0.2^{e}	13.3	12.7
$2.2 imes 10^{-5}$	14.8 ± 0.3	14.7	14.6
$3.4 imes 10^{-5}$	15.5 ± 0.4	15.7	16.1
2.7×10^{-4}	19.3 ± 0.3	17.7	19.3
$6.8 imes 10^{-4}$	20.5 ± 0.3	18.1	19.7
0.0005^{f}	19.9 ± 0.2	17.9	19.6
0.001	18.8 ± 0.3	18.3	19.7
0.005	19.9 ± 0.3	20.2	19.9
0.01	23.9 ± 0.5	22.5	
0.01	24.7 ± 0.3	22.5	
0.01	22.6 ± 0.3	22.5	
0.03	32.4 ± 0.3	31.8	
0.05	33.9 ± 0.6	41.0	
0.1	68.2 ± 1.0	64.2	
0.1	62.6 ± 1.0	64.2	
0.2	117 ± 2	111	
0.3	155 ± 6	157	
0.4	214 ± 3	203	
0.5	248 ± 1	249	
0.5	227 ± 1	249	
0.6	301 ± 3	206	
0.8	358 ± 5	388	
1.0	476 ± 7	481	
1.0	514 ± 5	481	

Table I Pseudo-First-Order Rate Constants (k_{obs}) for Hydrolysis of NPTH at Different [$^{-}$ OH]^a

^a [NPTH]₀ = 1×10^{-4} M, $\lambda = 260$ nm, ionic strength 1 M, 35°C and reaction mixture for each measurement contains 1% v/v CH₂CN.

^b Calculated from eq. (1) as described in the text.

° Calculated from the relationship $k_{calcd} = (ab [-OH])/(1 \times b[-OH])$ with $10^4a = 19.9 \text{ s}^{-1}$ and $10^{-5}b = 1.27 \text{ M}^{-1}$ (see text).

^d [-OH] = $(10_{w}^{(pH-pK)})/\gamma$ where desired pH was attained by carbonate buffers, $pK_{w} = 13.62$, and activity coefficient $\gamma = 0.7$ at 1 M ionic strength.

e Error limits are standard deviations.

^fHydroxide ion concentrations were maintained by using the stock solutions of NaOH.

The pK_a of 4-nitrophthalimide (NPTH) is expected to be significantly lower than that of phthalimide and consequently pH-independent hydrolysis of NPTH compared to that of phthalimide must occur at relatively lower [HO⁻]. The mechanism of a reaction remains essentially unchanged with the change in the reaction medium from pure aqueous to micelles, and the effects of ionic micelles on the rate of a reaction can be explained, at least in terms of polarity and ionic strength of the micellar surface. Thus, it becomes essential to study the reaction mechanism and the effects of mixed aqueous-organic solvents as well as ionic strength on the reaction rate before studying the effects of micelles on the same reaction rate. Thus, in order to find out the effect of $4 - NO_2$ group on the rate of cationic micellar-mediated alkaline hydrolysis of phthalimide and whether the PIE model is applicable, the rate of alkaline hydrolysis of NPTH has been studied in the absence and presence of cetyltrimethylammonium bromide (CTABr) micelles. The effects of mixed aqueous – organic solvents and ionic strength on the rate of alkaline hydrolysis of NPTH have been also studied in the absence of micelles. The observed results and their probable explanation(s) are described in this manuscript.

EXPERIMENTAL

Materials

All the chemicals used were supplied by Fluka, Sigma, or Aldrich and were of the highest commercially available purity. Buffer solutions of desired pH were freshly prepared. The stock solutions of NPTH were prepared in acetonitrile.

Kinetic Measurements

The rate of alkaline hydrolysis of NPTH was studied spectrophotometrically by monitoring the disappearance of the reactant NPTH at 260 nm. The observed data, absorbance (A_{obs}) versus reaction time (t), obeyed a pseudo-first-order rate law under the experimental conditions imposed. The details of the kinetic procedure and data analysis have been described elsewhere [7,14].

RESULTS

Effect of [NaOH] on k_{obs} (Pseudo-First-Order Rate Constant for Hydrolysis of NPTH)

A series of kinetic runs were carried out at different [NaOH] within its range 1.7×10^{-5} to 1.0 M at a constant ionic strength (1.0 M) and 35°C. Pseudo-first-order rate constants (k_{obs}) as summarized in Table I obeyed eq. (1):

$$k_{\rm obs} = \frac{ab[{\rm HO}^-] + bc[{\rm HO}^-]^2}{1 + b[{\rm HO}^-]}$$
(1)

where *a*, *b*, and *c* are unknown kinetic parameters. The nonlinear least-squares calculated values of *a*, *b*, and *c* are $(17.9 \pm 3.3) \times 10^{-4} \text{ s}^{-1}$, $(2.08 \pm 5.54) \times 10^{5} \text{ M}^{-1}$, and $(46.3 \pm 0.8) \times 10^{-3} \text{ M}^{-1} \text{ s}^{-1}$, respectively. The fitting of observed data to eq. (1) is evident from the values of rate constants (k_{calcd} , Table I) cal-

Cosolvent (X)	CH ₃ OH	CH ₃ CN
% v/v	$10^4 \ k_{\rm obs}/{\rm s}^{-1}$	$10^4 k_{\rm obs}/{\rm s}^{-1}$
5	21.2 ± 0.2^{b}	18.2 ± 0.1^{b}
10	18.5 ± 0.2	14.0 ± 0.2
20	13.0 ± 0.5	8.49 ± 0.07
30	10.9 ± 0.1	5.38 ± 0.4
40	8.33 ± 0.3	3.69 ± 0.03
50	6.24 ± 0.03	2.67 ± 0.02
60	4.52 ± 0.03	2.38 ± 0.03
70	3.29 ± 0.03	2.05 ± 0.04
80	2.12 ± 0.02	

Table II Pseudo-First-Order Rate Constants (k_{obs}) for Hydrolysis of NPTH at Different Contents (X) of Organic Cosolvents in Mixed Aqueous Solvents^a

^a [NPTH]₀ = 1 × 10⁻⁴ M, [NaOH] = 0.01 M λ = 260 nm, 35°C and reaction mixture for each measurement for *X* = CH₃OH contains 1% v/v CH₃CN.

^b Error limits are standard deviations.

culated from eq. (1) using the calculated values of kinetic parameters *a*, *b*, and *c*. The calculated value of *b* is statistically unreliable because its standard deviation is > 200%. A relatively more reliable value of *b* is expected to result by treating the observed data obtained within [HO⁻] range 1.7×10^{-5} to 5×10^{-3} , where the contribution of *bc*[HO⁻]² is negligible compared with *ab*[⁻OH] in eq. (1), with the equation $k_{obs} = ab$ [HO⁻]/(1 + *b*[HO⁻]). Such a data treatment gave $10^4a = 19.9 \pm 0.3 \text{ s}^{-1}$ and $10^{-5}b = 1.27 \pm 0.14 \text{ M}^{-1}$.

The [HO⁻] range of 1.7×10^{-5} to 6.8×10^{-4} M was achieved by the use of carbonate buffers. The values of k_{obs} remained unchanged with the change in the total concentration of carbonate buffer from 0.1 to 0.7 M at pH 10.2 ± 0.1. These results show that the pH-independent rate of hydrolysis of NPTH is insensitive to general base catalysis. The rate of alkaline hydrolysis of phthalimide [15] and *N*-hydroxyphthalimide [13] were found to be insensitive and sensitive, respectively, to general base catalysis.

Effect of Mixed CH₃CN-H₂O and CH₃OH-H₂O Solvents on k_{obs} at 0.01 M NaOH and 35°C

The rate of alkaline hydrolysis of NPTH was studied within the respective acetonitrile and methanol content range of 1 to 70 and 0 to 80% v/v in mixed aqueous solvents. Mixed aqueous–organic solvents were prepared by adding the appropriate amounts of water and organic cosolvent to the reaction mixtures. Pseudo-first-order rate constants (k_{obs}), as shown in Table II, revealed an approximately 11.6- and 11.3-fold de-

crease with the increase in CH_3CN content from 1 to 70% v/v and CH_3OH content from 0 to 80% v/v, respectively. These results may be qualitatively explained in terms of simple theories, such as that of Hughes and Ingold, and solvent polarity effect.

It should be noted that the presence of 0.01 M NaOH in CH₃OH solvent will generate CH₃O⁻ because the K_a values of CH₃OH and H₂O are nearly the same. Thus, the increase in the content of CH₃OH in mixed aqueous solvents will increase [CH₃O⁻] and decrease [HO⁻] because [CH₃O⁻] + [HO⁻] is constant (= 0.01 M). Although the nucleophilic reactivity of CH₃O⁻ toward electrophilic carbonyl carbon is nearly 60-fold larger than that of HO⁻, it has been shown elsewhere [14] that the rate constants k_{obs} are for hydrolysis and not for methanolysis of NPTH under the present experimental conditions.

Effect of [NaCl] on $k_{\rm obs}$ at 0.03 M NaOH and 35°C

In order to determine the effect of ionic strength on the rate of alkaline hydrolysis of NPTH, a few kinetic runs were carried out within the [NaCl] range 0.1-3.0M. The values of k_{obs} , as summarized in Table III, showed a mild increase (~27%) with the increase in the ionic strength from 0.03 to 3.0 M.

Effect of $[CTABr]_T$ on k_{obs} at Two Different [NaOH] and 35°C

A series of kinetic runs was carried out under varying total concentrations of cetyltrimethyl-ammonium bromide ([CTABr]_T) at 0.01 M NaOH in aqueous solvent containing 1% v/v CH₃CN. Several kinetic runs were also carried out at different [CTABr]_T and 0.05 M

Table III Pseudo-First-Order Rate Constants (k_{obs}) for Hydrolysis of NPTH at Different [NaCl]^a

[NaCl]/M	$10^4 \ k_{\rm obs}/{\rm s}^{-1}$
0.1	32.4 ± 0.3^{b}
0.4	34.3 ± 0.5
0.8	35.7 ± 0.6
1.2	36.8 ± 0.5
1.6	37.9 ± 0.5
2.0	38.6 ± 0.5
2.5	37.4 ± 0.6
3.0	41.1 ± 0.6

^a [NPTH]₀ = 1×10^{-4} M, [NaOH] = 0.03 M λ = 260 nm, 35°C and reaction mixture for each measurement contains 1% v/v CH₃CN.

^bError limits are standard deviations.

[NaOH]/M = 10 ⁴ [CTABr] _T M	0.01			0.05		
	$10^4 k_{\rm obs} \ {\rm s}^{-1}$	$10^4 k_{\rm calcd}{}^{\rm b} {\rm s}^{-1}$	$10^4 k_{\rm calcd}$ c s ⁻¹	$10^4 k_{\rm obs} \ {\rm s}^{-1}$	$10^4 k_{\text{calcd}}^{d} \text{ s}^{-1}$	$10^4 k_{\rm calcd}^{\rm e} {\rm s}^{-1}$
0.2	22.6 ± 0.3^{f}			33.9 ± 0.6^{f}		
0.4	22.6 ± 0.4			37.2 ± 0.5		
0.6	22.6 ± 0.3			36.6 ± 0.6		
1.0	22.8 ± 0.3			37.9 ± 0.4		
2.0	22.0 ± 0.5			34.2 ± 1.0	34.7	35.3
3.0	18.8 ± 0.6	17.6	17.5	24.1 ± 0.9	24.5	23.5
4.0	13.0 ± 0.3	12.6	12.6	19.8 ± 0.5	19.8	19.3
5.0	9.60 ± 0.2	10.1	10.1	17.4 ± 0.4	17.1	17.1
7.0	6.83 ± 0.05	7.62	7.63	13.5 ± 0.3	14.2	14.7
10.0	5.32 ± 0.06	5.98	5.99	12.9 ± 0.3	12.1	13.0
20.0	4.19 ± 0.05	4.26	4.26	10.7 ± 0.1	9.67	10.6
60.0	3.77 ± 0.07	3.20	3.20	8.57 ± 0.08	8.10	8.22
100.0	3.51 ± 0.05	3.00	3.00	7.57 ± 0.08	7.79	7.41
200.0	2.80 ± 0.03	2.85	2.85	6.23 ± 0.05	7.56	6.53
$10^{8} \Sigma d_{i}^{2}$	=	3.586	3.697		4.713	3.829
10 ⁴ cmc	$= 2.5 \text{ M}^{\text{g}} (2.7)$	1) ^h 1.8 M ^g (1.9 M) ^h				

Table IV Pseudo-First-Order Rate Constants (k_{obs}) for Hydrolysis of NPTH at Different [CTABr]_T and [NaOH]^a

^a [NPTH]₀ = 1 × 10⁻⁴ M, λ = 260 nm, 35°C, and reaction mixture for each measurement contains 1% v/v CH₃CN.

^b Calculated from eq. (3) with 10^4 cmc = 2.5 M, $10^4 k_W^{h}$ = 22.6 s⁻¹, $10^4 k_M^{h}$ = 2.71 s⁻¹, and K_s = 6769 M⁻¹.

° Calculated from eq. (5) with 10⁴ cmc = 2.5 M $K_{\rm Br}^{\rm OH}$ = 20, β = 0.8, 10⁴ $k_{0, \rm W}^{\rm h}$ = 17.9 s⁻¹, 10⁴ $k_{\rm OH, \rm W}^{\rm h}$ = 463 M⁻¹ s⁻¹, 10⁴ $k_{0,\rm M}^{\rm h}$ = 2.70 s⁻¹, 10⁴ $k_{\rm OH,\rm M}^{\rm msh}$ = 0, and $K_{\rm S}$ = 6710 M⁻¹.

^d Calculated from eq. (3) with 10⁴ cmc = 1.8 M, 10⁴ k_{W}^{h} = 36.4 s⁻¹, 10⁴ k_{M}^{h} = 7.33 s⁻¹, and K_{S} = 6333 M⁻¹.

^e Calculated from eq. (5) with 10⁴ cmc = 1.8 M, $K_{\rm Br}^{\rm OH} = 20$, $\beta = 0.8$, 10⁴ $k_{0,\rm W}^{\rm h} = 17.9 \text{ s}^{-1}$, 10⁴ $k_{\rm OH,W}^{\rm h} = 463 \text{ M}^{-1} \text{ s}^{-1}$, 10⁴ $k_{0,\rm M}^{\rm h} = 4.75 \text{ s}^{-1}$, 10⁴ $k_{0,\rm H,M}^{\rm msh} = 8.90 \text{ s}^{-1}$, and $K_{\rm S} = 11888 \text{ M}^{-1}$.

^fError limits are standard deviations.

^g The values of cmc were obtained from graphical technique [23].

^h Parenthesized values were obtained from iterative technique [22] using eq. (3).

NaOH. The observed data $(k_{obs} \text{ vs. } [CTABr]_T)$ are shown in Table IV.

DISCUSSION

The change in k_{obs} with the change in [NaOH] (Table I) may be explained through a reaction mechanism as



shown in Scheme I. A similar mechanism has been found to occur in several related reactions under essentially similar experimental conditions. The observed rate law (rate = k_{obs} [NPTH]_T, where [NPTH]_T = [NPTH] + [NPT⁻]), and Scheme I can lead to eq. (2):

$$k_{\rm obs} = \frac{k_0 K_i [\rm HO^-] + k_{\rm OH} K_i [\rm HO^-]^2}{1 + K_i [\rm HO^-])}$$
(2)

where $k_0 = k'_{OH} K_w/K_a$, with $K_a = [NPT^-][H^+]/[NPTH]$ and $K_w = [H^+][HO^-]$ and $K_i = K'_i/[H_2O] = K_a/K_w$. The occurrence of a reaction step for rate law $k_w[H_2O][NPT^-]$, which is kinetically indistinguishable from the reaction step for rate law $k'_{OH}[HO^-][NPTH]$, may be ruled out based on evidence described elsewhere [16]. Similarly, the notion that the rate of hydrolysis of NPTH at considerably high values of [NaOH] does not involve NPT⁻ as reactive species may be shown to be incorrect based on kinetic evidence discussed elsewhere [17].

Equation (2) is similar to eq. (1), with $k_0 = a$,

 $K_i = b$, and $k_{OH} = c$. The value of k_{OH} (= 0.0463) M^{-1} s⁻¹) is nearly 12-fold larger than k_{OH} (= 3.84 × 10^{-3} M⁻¹ s⁻¹) for phthalimide, which may be attributed to the favorable substituent effect exerted by the nitro group in NPTH. It is interesting to note that the values of k_{obs} ($\approx 20 \times 10^{-4} \text{ s}^{-1}$, Table I) in the pHindependent rate region are even slightly smaller than the corresponding k_{obs} (= 24 × 10⁻⁴ s⁻¹) for phthalimide [18]. These results can be explained if the pHindependent rate of hydrolysis is governed by the rate law $k'_{OH}[OH^{-}][NPTH]$ only. Under such conditions, $k_{\rm obs} = k'_{\rm OH} K_{\rm w} / K_{\rm a}$, and hence it is possible that the ratio k'_{OH}/K_a for NPTH may not be significantly different from k'_{OH}/K_a for phthalimide if the substituent (NO₂) effects on both k'_{OH} and K_a are nearly the same in magnitude. The calculated values of $k'_{OH} = k_0 K_i$ 253 M⁻¹ s⁻¹) and K_a (= $K_i K_w = 3.1 \times 10^{-9}$ M with $K_{\rm w} = 2.4 = 10^{-14} \,\text{M}^2$ at 35°C [19]) are nearly 5- and 7-fold, respectively, larger than the corresponding values of k'_{OH} (= 53 M⁻¹ s⁻¹) and K_a (= 4.3 × 10⁻¹⁰ M) for phthalimide. These results are conceivable from the fact that the NO₂ group is a powerful electronwithdrawing group compared with H, and hence the NO_2 group must increase K_a . The electron-withdrawing NO₂ group is expected to increase both the electrophilicity of carbonyl carbon and the leaving ability of the leaving group in NPTH, and consequently it increases the rate of reaction of HO- with NPTH (Scheme I) compared with phthalimide.

The rate constant k'_{OH} is not expected to be affected by the ionic strength because k'_{OH} is the second-order rate constant for a reaction involving a neutral and an ionic reactant [20]. But the rate constant k_{OH} (for a bimolecular reaction involving two ionic reactants) should be affected by the ionic strength. The nearly 26% increase in k_{obs} due to the increase in ionic strength from 0.03 to 3.0 M is possibly due to the ionic strength effect on k_{OH} , because at 0.03 M NaOH, the contribution of $k_{OH}K_i[HO^-]^2$ compared to $k_0K_i[HO^-]$ in eq. (2) is ~41%.

The effects of mixed aqueous–organic solvents were studied at 0.01 M NaOH, and under such conditions, the contribution of $k_{OH}K_i[HO^-]^2$ in eq. (2) is only 19%. Thus, 81% of the contribution to k_{obs} comes from $k_0K_i[HO^-]$, and the reactions that obey such a rate law are known to be inhibited by the increase in the content of organic cosolvent in mixed aqueous solvents. Pseudo-first-order rate constants for alkaline hydrolysis of phenyl benzoate decreased by slightly more than 10-fold with the increase in CH₃CN content from 2 to 70% v/v in mixed aqueous solvent [21].

The increase in $[CTABr]_T$ from $\sim 3 \times 10^{-4}$ to 0.02 M resulted in an approximately monotonic decrease in k_{obs} at both 0.01 and 0.05 M NaOH (Table IV). Such results have been generally explained, to a first ap-

proximation, in terms of pseudophase model (PM) of micelle [9]. The PM model can lead to eq. (3):

$$k_{\rm obs} = \frac{k_{\rm W}^{\rm h} + k_{\rm M}^{\rm h} K_{\rm S}[D_n]}{1 + K_{\rm S}[D_n]}$$
(3)

where $k_{\rm W}^{\rm h}$ and $k_{\rm M}^{\rm h}$ represent pseudo-first-order rate constants for hydrolysis of NPTH in the aqueous pseudophase and micellar pseudophase, respectively; K_s is the micellar binding constant of NPTH; and $[D_n] =$ $[CTABr]_T - cmc$, with cmc representing critical micelle concentration. The value of cmc was obtained by using both iterative [22] and graphical [23] techniques. The values of cmc at different [NaOH] are summarized in Table IV. The value of k_{w}^{h} was taken as the average value of k_{obs} obtained at $[CTABr]_T < cmc$. The unknown kinetic parameters, $k_{\rm M}^{\rm h}$ and $K_{\rm S}$ were calculated from eq. (3) using the nonlinear least-squares technique. The calculated respective values of $k_{\rm M}{}^{\rm h}$ and $K_{\rm S}$ are $(2.71 \pm 0.38) \times 10^{-4} \, {\rm s}^{-1}$ and 6770 \pm 680 M⁻¹ at 0.01 M NaOH and $(7.33 \pm 0.41) \times$ 10^{-4} s^{-1} and 6330 ± 460 M⁻¹ at 0.05 M NaOH. The fitting of the observed data to eq. (3) appears to be satisfactory, as evident from the standard deviations associated with the calculated kinetic parameters and from the k_{calcd} values listed in Table IV.

The occurrence of ion exchange in ionic micellarmediated ionic or semi-ionic reactions has been unequivocally established [24-28]. The possible ion-exchange processes in the present reacting system are Br⁻/HO⁻, Br⁻/NPT⁻, and NPT⁻/HO⁻. But the ion-exchange processes Br⁻/NPT⁻ and NPT⁻/HO⁻ may be ignored compared with Br⁻/HO⁻ due to the fact that the maximum concentration of NPT- was kept at a relatively very small level (1 \times 10⁻⁴ M), and the difference in hydrophobicity of NPT- and HO- or Brshould be very large. Thus, the most effective ion exchange, in the present experimental conditions, is Br⁻/HO⁻. The k_{obs} versus [CTABr]_T profile for such reactions is generally explained in terms of the pseudophase ion-exchange (PIE) model [2,3,10]. In view of the PIE model, the concentrations of HO- (ionic reactant) and Br- (counterion) in the micellar and aqueous pseudophase are generally governed by an ion-exchange equilibrium, eq. (4):

$$K_{\rm Br}^{\rm OH} = ([{\rm HO}_{\rm W}^{-}][{\rm Br}_{\rm M}^{-}])/([{\rm HO}_{\rm M}^{-}][{\rm Br}_{\rm W}^{-}]) = ([{\rm HO}_{\rm W}^{-}]m_{\rm Br})/(m_{\rm OH}[{\rm Br}_{\rm W}^{-}])$$
(4)

where the subscripts W and M represent aqueous and micellar pseudophase, respectively, $m_{\rm Br} =$ [Br_M⁻]/[D_n] and $m_{\rm OH} =$ [HO_M⁻]/[D_n].

The reaction scheme, in terms of PM model, can lead to eq. (5):

$$k_{\rm obs} = \frac{k_{\rm 0,W}^{\rm h} + k_{\rm OH,W}^{\rm h}[{\rm HO}_{\rm W}^{-}] + (k_{\rm 0,M}^{\rm h} + k_{\rm OH,M}^{\rm msh}m_{\rm OH})K_{\rm S}[D_n]}{1 + K_{\rm S}(D_n)}$$
(5)

where $k_{\text{OH,M}}^{\text{msh}} = k_{\text{OH,M}}^{\text{h}} V_{\text{M}}$, with V_{M} representing micellar molar volume [2,3], $k_{0,\text{W}}^{\text{h}}$ and $k_{0,\text{M}}^{\text{h}}$ represent first-order rate constants for pH-independent hydrolysis of NPTH and $k_{\text{OH,W}}^{\text{h}}$ and $k_{\text{OH,M}}^{\text{h}}$ are second-order rate constants for the reactions of HO⁻ with ionized NPTH in aqueous and micellar pseudophase, respectively.

The values of m_{OH} at different $[D_n]$ were obtained from a kinetic equation derived from PIE formalism [2,3,10]. The value of β (= fraction of counterions bound to micelle) and $K_{\rm Br}^{\rm OH}$ were considered to be 0.8 and 20, respectively, and $k_{0.W}^{h}$ (= 17.9 × 10⁻⁴ s⁻¹) and $k_{OH,W}^{h}$ (= 0.0463 M⁻¹ s⁻¹) were obtained by carrying out the experiments in the absence of micelles. The unknown parameters, $k_{0,M}^{h}$, $k_{OH,M}^{msh}$, and K_{S} were calculated from eq. (5) using the nonlinear leastsquares technique. The respective values of $k_{0,M}^{h}$, $k_{\rm OHM}^{\rm msh}$, and $K_{\rm S}$ are $(3.80 \pm 0.64) \times 10^{-4} \, {\rm s}^{-1}$, $(-8.9 \pm 4.8) \times 10^{-4} \text{ s}^{-1}$, and $4900 \pm 860 \text{ M}^{-1}$ at 0.01 M NaOH and $(4.75 \pm 0.91) \times 10^{-4} \text{ s}^{-1}$, $(8.90 \pm 2.42) \times 10^{-4} \text{ s}^{-1}$, and $11888 \pm 1494 \text{ M}^{-1}$ at 0.05 M NaOH. The negative value of k_{OHM}^{msh} at 0.01 M NaOH is physically and chemically meaningless. Thus, relatively more reliable values of $k_{0,M}^{h}$ and K_{S} at 0.01 M NaOH were calculated from eq. (5) by setting $k_{\text{OH,M}}^{\text{msh}} = 0$. The calculated values of $k_{0,\text{M}}^{\text{h}}$ and K_{s} at $k_{\text{OH,M}}^{\text{msh}} = 0$ are (2.70 ± 0.39) × 10⁻⁴ s⁻¹ and $6710 \pm 683 \text{ M}^{-1}$, respectively. The contribution of $k_{\rm OH,W}^{\rm h}$ [HO_W⁻] compared with $k_{0,W}^{\rm h}$ is nearly 19% at 0.01 M NaOH. The least-squares ($\sum d_i^2$ where $d_i =$ $k_{\text{obs }i} - k_{\text{calcd }i}$) value obtained from eq. (3) is similar to one obtained from eq. (5) with $k_{OH,M}^{msh} = 0$. It may be noted that the change in $K_{\rm Br}^{\rm OH}$ from 15 to 100 at $\beta = 0.8$ and in β from 0.8 to 0.2 $K_{\rm Br}^{\rm OH} = 20$ did not reveal an appreciable change in $\sum d_i^2$ values. Thus, the characteristic that $k_{OH,M}^{msh} = 0$ indicates that ion-exchange Br⁻/HO⁻ could not produce enough [HO_M⁻] to make $k_{OH,M}$ ^{msh} m_{OH} significant compared with $k_{0,M}$ ^h in eq. (5).

The contribution of $k_{OH,W}^{h}$ [HO_w⁻] compared with $k_{0,W}^{h}$ is nearly 56% at 0.05 M NaOH. The data treatment with eq. (5) resulted in a change in Σd_i^2 from 3.823 × 10⁻⁸ to 3.737 × 10⁻⁸, in $k_{0,M}^{h}$ from 4.00 × 10⁻⁴ to 5.68 × 10⁻⁴ s⁻¹, in $k_{OH,M}^{msh}$ from 8.72 × 10⁻⁴ to 13.6 × 10⁻⁴ s⁻¹, and in $K_{\rm S}$ from 11313 to 13850 M⁻¹ with the change in β from 0.8 to 0.2 at $\beta = 0.8$. Similarly, the change in β from 0.8 to 0.2 at $K_{\rm Br}^{OH} = 20$ revealed the change in Σd_i^2 from 3.829 × 10⁻⁸ to 4.024 × 10⁻⁸, in $k_{0,M}^{h}$ from 4.75 × 10⁻⁴ to 5.71 × 10⁻⁴ s⁻¹, in $k_{OH,M}^{msh}$ from 8.72 × 10⁻⁴ to 3.0.3 × 10⁻⁴ s⁻¹, and in $K_{\rm S}$ from 11888 to

11897 M⁻¹. Thus, based on the criterion that the best data fit is the one for which the value of ΣD_i^2 is the least, it is not possible to ascertain the most appropriate values of $K_{\rm Br}^{\rm OH}$ and β . Such uncertainty in the use of the PIE model is not due to ignoring the other possible ion-exchange processes (NPT-/Br- and NPT-/HO-) because similar uncertainty was encountered in the data treatment of alkaline hydrolysis of securinine, which involved only one ion-exchange Br⁻/HO⁻ [29]. This is an apparent weakness in the PIE model, as reported by other workers [30,31]. The value of $k_{\text{OH,W}}^{\text{h}}$ (=0.04 M⁻¹ s⁻¹) for securinine is not significantly different from $k_{OH,W}^{h}$ (= 0.046 M⁻¹ s⁻¹) for NPT-. However, nonkinetic experimental methods gave the values of $K_{\rm Br}^{\rm OH}$ and β as 7–31 and 0.8, respectively [10]. The value of $\sum d_i^2$ obtained for the data treatment with eq. (5) at $K_{\rm Br}^{\rm OH} = 20$ and $\beta = 0.8$ is nearly 20% lower than that with eq. (3) at 0.05 M NaOH (Table IV). This shows that the ion-exchange Br⁻/HO⁻ is kinetically significant at 0.05 M NaOH (i.e., k_{OHM}^{msh} does not seem to be negligible). But the derived values of $k_{0,M}^{h}$, $k_{OH,M}^{msh}$, and K_S from eq. (5) are not very reliable because of the probable uncertainties in the chosen values of $K_{\rm Br}^{\rm OH}$ (= 20) and β (=0.8).

The value of $K_{\rm S}$ (= 6600 M⁻¹) is nearly 2.5-fold larger than $K_{\rm s}$ (= 2600 M⁻¹) for phthalimide [7]. The CTABr micellar surface affinity of the m-nitrobenzoate ion is nearly 3-fold larger than that of the o- or p-nitrobenzoate ion [28]. The reason for the low cationic micellar surface affinity of the *p*-nitrobenzoate ion is attributed to the significant polarity of the nitro group. The relative cationic micellar surface affinity of o-m-, and p-nitrobenzoate ions is not yet fully understood. The structural location of the nitro group in NPTH roughly corresponds to in between the p- and *m*-nitrobenzoate ions. Kinetic data revealed a nearly 1.4-fold larger affinity of the benzoate ion [32] compared to the o- and p-nitrobenzoate ion [28] toward cationic micelles. Thus, a \sim 2.5-fold larger value of $K_{\rm S}$ for NPTH compared to $K_{\rm S}$ for phthalimide is conceivable in view of the effect of the nitro group on $K_{\rm s}$.

A skeptic might think that cationic micelles are often used to increase the rate of hydrolysis reactions, whereas the reverse is observed here. Ionic micelles can increase the rate of a bimolecular reaction involving one or both reactant molecules as ions with charge similar to the charge of counterions under one, or more than one, of the following circumstances. (a) Micelles cause an increase in the concentration of reactants into

the micellar phase by strongly binding the reactant(s). (b) The rate of a reaction is either insensitive to the polarity change or increases with the decrease in the polarity of the reaction medium. (c) Both reactants have the same site of average location into the micellar phase. (d) The magnitude of the second-order rate constant for a fully or semi-ionic bimolecular reaction into the micellar phase should be sufficiently large to cause a rate-increasing effect due to the increase in the concentration of micellized ionic reactant(s) through the usual ion-exchange process. (e) Micelles stabilize the transition state more strongly than the reactant state in a critical rate-determining step of the reaction. In the present reaction system, the rate constants k_{0M}^{h} and $k_{0,W}^{h}$ should not be affected by the occurrence of HO⁻/Br⁻ ion exchange because these rate constants stand for pH-independent hydrolysis of NPTH. Although we do not know the exact value of $k_{OH,M}^{h}$, its value must be proportional to $k_{OH,W}^{h}$, and the value of $K_{\text{OH,W}}^{\text{h}}$ is 0.0463 M⁻¹ s⁻¹. Rate maxima in k_{obs} – [CTABr]_T profiles were obtained in the reactions of HO⁻ with ionized N-hydroxyphthalimide [11] (where $k_{\text{OH W}}^{\text{h}} = 0.56 \text{ M}^{-1} \text{ s}^{-1}$) and with phenyl benzoate [21] (where $k_{OH,W}^{h} = 0.68 \text{ M}^{-1} \text{ s}^{-1}$), whereas such maxima were not obtained in the reactions of HOwith neutral securinine [29] (where $k_{OH,W}^{h} = 0.04$ M^{-1} s⁻¹). It is thus apparent that the absence of a rateincreasing effect of CTABr micelles in the present reaction is due to rather low values of $k_{OH,W}^{h}$ and hence $k_{\rm OH,M}^{\rm h}$.

Ionic micellar-mediated organic reactions are believed to occur either inside the Stern layer or at the interface between the micellar surface and bulk water solvent. The concentration of charged groups at the ionic micellar surface, although very uncertain, is nearly 3.5 M [35]. The increase in [NaCl] from 0 to 3.0 M increased k_{obs} from 32×10^{-4} s⁻¹ to $41 \times$ 10^{-4} at 0.03 M NaOH (Table III). Thus, micellar inhibition of the hydrolysis of NPTH at both 0.01 and 0.05 M NaOH cannot be explained in terms of a micellar surface ionic strength effect.

The polarity of the micellar surface has been shown to be considerably smaller compared to that of aqueous pseudophase [36–40]. The increase in the contents of CH₃CN and CH₃OH from 1 to 70% v/v decreased k_{obs} by ~ 11-fold (Table II). It is therefore tempting to propose that micellar inhibition of hydrolysis of NPTH at both 0.01 and 0.05 M NaOH is merely due to the medium polarity effect. However, micellar inhibition due to different sites of average location of both the reactants (NPTH_M and HO_M⁻, as well as NPT_M⁻ and HO_M⁻) at the micellar surface cannot be completely ruled out [41,42].

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