

no formation of *cis*-9c was observed. In a parallel run with 0.69 *M cis*-9c, 0.66 *M* 8, 0.44 *M* toluene, and 0.048 *M* AIBN, no formation of *trans*-9c was observed up to 90% consumption of 8. The initial distribution among products J-M was quite different in the two runs, and each also changed noticeably with extent of conversion.

**Reaction of 2-Hexen-4-yne (9d) with Trimethyltin Hydride (8).** A mixture of 1.85 g (23.1 mmol) of enyne 9d (largely *cis*), 2.79 g (16.9 mmol) of stannane 8, and 0.16 g (0.98 mmol) of AIBN was heated in a sealed tube at 85° for 21 hr; glpc analysis revealed only a trace of residual 8. Evaporation and distillation gave 1.65 g (40%), bp 55° (2.3 Torr), of product whose glpc spectrum (Apiezon L) was very similar to that before distillation and showed three resolved peaks in a ratio of 46:17:37. The nmr spectrum had a broad multiplet at 7.1–5.3, three broadened lines at 2.03, 1.90, and 1.80, and two singlets at 0.30 and 0.22 ppm with areas consistent for

this product's being mixed geometrical isomers of 2,4-hexadien-2-yltrimethyltin (23). However, a weak ir band at 1925  $\text{cm}^{-1}$  both in the crude and distilled products again indicates a minor adduct with allenic structure.

A mixture of 1.69 g (21.1 mmol) of enyne 9d (*cis/trans* = 1.5), 2.42 g (14.7 mmol) of stannane 8, and 0.15 g (0.93 mmol) of AIBN was irradiated with a high-pressure mercury lamp through Pyrex for 24 hr at 25°. Glpc analysis revealed no residual 8 and a mono-adduct pattern very similar to that from the thermal reaction described above. Distillation gave 2.33 g (65%), bp 47–52° (2 Torr), of mixed adducts with an nmr spectrum very similar to that described above.

A pair of parallel experiments to probe for isomerization of unreacted enyne 9d as a function of extent of consumption of stannane 8 was carried out at 60° in xylene solvent, and results are described in Table V.

## Apolar Influences in the Poly[4(5)-vinylimidazole] Catalyzed Hydrolyses of 3-Nitro-4-acyloxybenzoic Acid Substrates

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**Abstract:** The effects of the acyl chain length in the substrate and volume per cent of water in the aqueous-alcohol solvent systems on the rate of hydrolysis of 3-nitro-4-acyloxybenzoic acid substrates ( $S_n^-$ ) catalyzed by imidazole (Im) and poly[4(5)-vinylimidazole] (PVIm) were determined. They demonstrate the importance of apolar bonding in the rate enhancements observed for PVIm catalyzed reactions as compared to Im catalyzed reactions. The critical micelle concentrations (cmc) of the substrates in aqueous-alcohol solutions were determined spectroscopically. Knowledge of cmc values permitted a more meaningful interpretation of the kinetic data. In certain esterolysis reactions, deviations from pseudo-first-order kinetics were observed. With  $[S_n^-] > [\text{PVIm}]$  in 15 and 20% 1-propanol-water systems, the kinetic behavior exhibited was indicative of "saturation" of the polymer with substrate. When  $[\text{PVIm}] > [S_n^-]$  cases were studied in 20% 1-propanol in water systems, an analogous saturation of the substrate with polymer was indicated by the kinetic behavior. The effect of varying the pH and temperature on these esterolysis reactions was also studied. An increase in  $r$  ( $r = k_{\text{PVIm}}/k_{\text{Im}}$ ) was observed with decreasing pH.

Recently there has been considerable success in utilizing apolar (or hydrophobic) forces to enhance the esterolytic action of synthetic macromolecular catalysts,<sup>1–5</sup> as well as monomeric catalysts.<sup>6,7</sup> In some cases it has been possible to observe saturation kinetics, formally characteristic of a catalyst-substrate complex, as is observed in enzyme-catalyzed reactions.<sup>1,3–5</sup> Although the kinetic formalism is similar, the process is obviously different than that

exhibited by an enzyme. Apolar interactions were also responsible for the dramatic rate enhancements observed for the poly[4(5)-vinylimidazole] (PVIm) catalyzed hydrolysis of the long-chain, anionic substrate 3-nitro-4-dodecanoyloxybenzoic acid ( $S_{12}^-$ ), relative to monomeric imidazole (Im).<sup>2</sup>

We would now like to report the results of the PVIm catalyzed esterolyses of a series of anionic esters in varying alcohol-water solvent systems. The ester substrates differ only in the chain length of the acid portion of the ester.

### Results and Discussion

The rates of hydrolysis of a series of 3-nitro-4-acetyloxybenzoic acid substrates ( $S_n^-$ ) catalyzed by PVIm were observed in varying volume per cent alcohol-water solvent systems. This series of substrates was selected to allow a controlled qualitative variation of the apolar forces operating during the hydrolysis. Previous results on the PVIm catalyzed hydrolysis of  $S_{12}^-$  in ethanol-water solvent systems indicated that these apolar forces would be substantial<sup>1</sup> with long-chain substrates.

**Critical Micelle Concentration of  $S_n^-$ .** A prereq-

(1) C. G. Overberger and M. Morimoto, *J. Amer. Chem. Soc.*, **93**, 3222 (1971); C. G. Overberger, M. Morimoto, I. Cho, and J. C. Salamone, *ibid.*, **93**, 3228 (1971).

(2) C. G. Overberger, M. Morimoto, I. Cho, and J. C. Salamone, *Macromolecules*, **2**, 553 (1969).

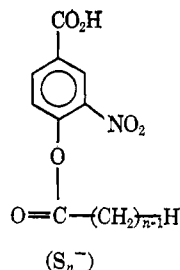
(3) C. Aso, T. Kunitake, and F. Shimada, *J. Amer. Chem. Soc.*, **91**, 2716 (1969); T. Kunitake and S. Shinkai, *ibid.*, **93**, 4247, 4256 (1971).

(4) Y. E. Kirsh, V. A. Kabanov, and V. A. Kargin, *Dokl. Chem.*, **177**, 976 (1967); S. K. Pluzhnikov, Y. E. Kirsh, V. A. Kabanov, and V. A. Kargin, *ibid.*, **185**, 291 (1969).

(5) I. M. Klotz and V. H. Stryker, *J. Amer. Chem. Soc.*, **90**, 2717 (1968); I. M. Klotz and G. P. Royer, *ibid.*, **91**, 5885 (1969); I. M. Klotz, G. P. Royer, and A. R. Sloniewsky, *Biochemistry*, **8**, 4752 (1969); I. M. Klotz, G. P. Royer, and I. S. Scarpa, *Proc. Nat. Acad. Sci., U. S. A.*, **68**, 263 (1971).

(6) C. Aso, T. Kunitake, and S. Shinkai, *Chem. Commun.*, 1483 (1968); T. Kunitake and S. Shinkai, *Bull. Chem. Soc. Jap.*, **43**, 1109 (1970); S. Shinkai and T. Kunitake, *ibid.*, **44**, 3086 (1971).

(7) C. A. Blyth and J. R. Knowles, *J. Amer. Chem. Soc.*, **93**, 3017, 3021 (1971).



$n = 2, 7, 12, \text{ and } 18$

quisite to the study of the hydrolytic behavior of  $S_n^-$  is a knowledge of their physical state in solution. These substrates can be expected to aggregate in aqueous solution with formation of premicelles or micelles.<sup>8,9</sup> Accompanying micelle formation is an abrupt, almost discontinuous change in many solution properties; these include surface tension, viscosity, light scattering, conductivity, the ability to solubilize certain dyes, etc. Any of these properties may be utilized to determine the critical micelle concentration (cmc) for a particular surfactant under certain conditions. The absorbance behavior of the dye pinacyanol chloride has frequently been used to determine the cmc of anionic detergents.<sup>10</sup> Although this spectral change method has been shown to be somewhat inaccurate,<sup>11</sup> it provided a minimum value for the cmc which was satisfactory for the purposes of this study.

Table I gives the pertinent cmc data for  $S_n^-$  in vary-

**Table I.** Critical Micelle Concentrations (cmc) of  $S_n^-$  in Varying Alcohol-Water Solvent Systems<sup>a</sup>

Alcohol	Vol % alcohol-water	Cmc $\times 10^5 M$		
		$S_7^-$	$S_{12}^-$	$S_{18}^-$
EtOH	20	>700	60	4.8
EtOH	30		>700	9.8
EtOH	40			700
1-PrOH	10	650	8.0	
1-PrOH	15		15	10
1-PrOH	20		54	19

<sup>a</sup>  $\mu = 0.02$ , [Tris] = 0.02 M, pH 8.0, 26°.

ing volume per cent ethanol-water and 1-propanol-water solvent systems. The solution properties and solvent compositions are those employed in the kinetic experiments. The cmc values increased for a particular substrate as the alcohol content of the solvent increased. The apolar forces responsible for micelle formation are disrupted in the higher alcohol compositions.<sup>12</sup> Thus, for  $S_{18}^-$  the cmc increased from  $4.8 \times 10^{-5} M$  in 20 vol % ethanol-water to greater than  $700 \times 10^{-5} M$  in 40%. Also, as the chain length of the substrate was increased in a particular solvent composition, the cmc decreased. In 20 vol % ethanol-

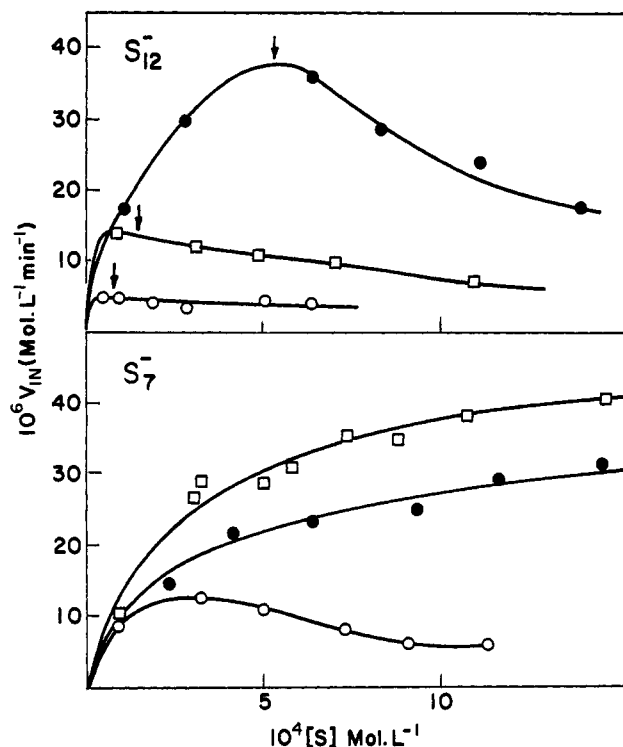


Figure 1. PVIm catalyzed initial esterolysis rates of  $S_7^-$  and  $S_{12}^-$  in 10 vol % (○), 15 vol % (□), and 20 vol % (●) 1-propanol-water; [PVIm] =  $5.0 \times 10^{-5} M$ ,  $\mu = 0.02$ , [Tris] = 0.02 M, pH 8.0, 26°. Arrows indicate experimentally determined cmc value via pinacyanol chloride method.

water the cmc for  $S_7^-$  was greater than  $700 \times 10^{-5} M$ , but decreased to  $4.8 \times 10^{-5} M$  for  $S_{18}^-$  in the same solvent. This observation is consistent with the fact that micelles are held together by apolar forces which increase as the chain length of the substrate is increased.<sup>8</sup> The same trends were observed in 1-propanol-water. In all kinetic experiments reported, the concentration of substrate used was below the cmc, unless otherwise indicated. Thus, during the course of this investigation it was possible to focus on any apolar interaction involved in the catalysis without complications due to micellar effects.

A kinetic verification of the cmc values was also obtained. In the plots of initial velocity ( $v_{in}$ ) vs.  $[S_n^-]$ , a bell-shaped profile was observed in several cases. The maximum was very near the cmc of the substrate as determined by the spectral change method (see Figure 1). Thus, the decrease of the reaction rate was attributable to progressive micellarization of the substrate.

**Hydrolysis of  $S_n^-$  Catalyzed by Imidazole (Im).** Tables II and III show the results of the Im catalyzed hydrolysis of  $S_n^-$  in varying volume per cent ethanol-water and 1-propanol-water solvent systems. In a particular solvent composition, the second-order rate constants ( $k_{cat}$ ) decreased as the chain length of the substrate increased. Steric hindrance to Im attack at the carbonyl carbon by the alkyl chain of the acyl portion of the substrates can explain this observation. This type of steric effect has been discussed by Taft<sup>13</sup> in general terms and demonstrated by Fife<sup>14</sup> for the Im

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(9) P. Mukerjee, *Advan. Colloid Interface Sci.*, **1**, 241 (1967).

(10) M. L. Corrin, H. B. Kleven, and W. D. Harkins, *J. Chem. Phys.*, **14**, 480 (1946); F. M. Menger and C. E. Portnoy, *J. Amer. Chem. Soc.*, **89**, 4698 (1967).

(11) P. Mukerjee and K. J. Mysels, *J. Amer. Chem. Soc.*, **77**, 2937 (1955).

(12) W. P. Jencks, "Catalysis in Chemistry and Enzymology," McGraw-Hill, New York, N. Y., 1969.

(13) R. W. Taft in "Steric Effects in Organic Chemistry," M. S. Newman, Ed., Wiley, New York, N. Y., 1956, p 597.

(14) T. H. Fife, *J. Amer. Chem. Soc.*, **87**, 4597 (1965).

**Table II.** Influence of Composition of Ethanol–Water Mixtures on the Apparent Second-Order Rate Constants ( $k_{\text{cat}}$ ) for the PVIm and Im Catalyzed Hydrolyses of  $\text{S}_n^-$ 

$k_{\text{cat}}, M^{-1} \text{ min}^{-1}$ Sub- strate	Cata- lyst	Vol % ethanol–water <sup>a</sup>				
		20 <sup>c</sup>	25	33	40	60
$\text{S}_2^-$	PVIm	338.0	95.2	73.0	43.1	19.3
	Im	57.8	45.4	37.6	16.9	5.9
	$r^b$	5.8	2.1	2.0	2.5	3.3
$\text{S}_7^-$	PVIm	2038 <sup>d,e</sup>	366 <sup>d</sup>	63.6	25.6	6.3
	Im	30.4	22.0	15.7	6.8	2.4
	$r$	67.0	16.6	4.0	3.8	2.6
$\text{S}_{12}^-$	PVIm	10,316 <sup>d,e</sup>	5316 <sup>d,e</sup>	1100 <sup>d,e</sup>	174 <sup>d</sup>	5.5
	Im	26.3	20.2	11.4	5.5	2.9
	$r$	392	264	61.4	31.6	1.9
$\text{S}_{18}^-$	PVIm			1200 <sup>e</sup>	1000 <sup>d,e</sup>	
	Im	2.9 <sup>f</sup>	5.2	5.2	5.7	
	$r$			237	175	

<sup>a</sup> [PVIm] = [Im] =  $5.0 \times 10^{-4} M$ ,  $[\text{S}_n^-] = 5.0 \times 10^{-5} M$ ,  $\mu = 0.02$ , [Tris] =  $0.02 M$ , pH = 8.0, 26°. <sup>b</sup>  $r = k_{\text{cat}}^{\text{PVIm}}/k_{\text{cat}}^{\text{Im}}$ . <sup>c</sup> Polymer solution became turbid on standing. <sup>d</sup> Accelerative kinetic behavior; rate constant determined at ca. 75% reaction. <sup>e</sup> Determined by the method of stopped-flow spectroscopy. <sup>f</sup> Concentration of substrate above cmc.

**Table III.** Influence of 1-Propanol–Water Mixtures on the Apparent Second-Order Rate Constants ( $k_{\text{cat}}$ ) for the PVIm and Im Catalyzed Hydrolyses of  $\text{S}_n^-$ 

$k_{\text{cat}}, M^{-1} \text{ min}^{-1}$ Sub- strate	Cata- lyst	Vol % 1-propanol–water <sup>a</sup>				
		15 <sup>c</sup>	20	25	30	40
$\text{S}_2^-$	PVIm	297	145.5	89.5	59.5	34.2
	Im	65.5	44.5	30.0	17.3	10.2
	$r^b$	4.6	3.3	3.0	3.4	3.4
$\text{S}_7^-$	PVIm	3100 <sup>e</sup>	192.4	43.0	19.7	8.3
	Im	63.3	24.4	9.4	4.8	2.8
	$r$	49.0	8.0	4.6	4.1	3.0
$\text{S}_{12}^-$	PVIm	10,200 <sup>e,f</sup>	3830 <sup>d,e</sup>	297 <sup>d</sup>	17.7	5.3
	Im	24.9	12.2	8.2	4.7	2.7
	$r$	410	314	36.3	3.8	2.0
$\text{S}_{18}^-$	PVIm		6085 <sup>e,f</sup>	1075 <sup>d,e</sup>	276 <sup>d</sup>	6.3
	Im		5.2	6.2	4.7	2.0
	$r$		1170	172	58.9	2.3

<sup>a</sup> [PVIm] = [Im] =  $5.0 \times 10^{-4} M$ ,  $[\text{S}_n^-] = 5.0 \times 10^{-5} M$ ,  $\mu = 0.02$ , [Tris] =  $0.02 M$ , pH = 8.0, 26°. <sup>b</sup>  $r = k_{\text{cat}}^{\text{PVIm}}/k_{\text{cat}}^{\text{Im}}$ . <sup>c</sup> Polymer solution is turbid. <sup>d</sup> Accelerative kinetic behavior. <sup>e</sup> Determined by the method of stopped-flow spectroscopy. <sup>f</sup> Kinetics with turbidity formation near the end of reaction;  $k_{\text{cat}}$  determined in unperturbed region.

catalyzed hydrolysis of a series of alkyl esters of *p*-nitrophenol. Also, the rates of hydrolyses increased with decreasing ethanol (or 1-propanol) content of the solvent for all substrates, except  $\text{S}_{18}^-$ . This trend is a result of the hydrolyses being facilitated by solvation of the transition state as the polarity of the solvent mixture increases. However, for  $\text{S}_{18}^-$  the rate constant decreased as the ethanol content of the solvent dropped below 25 vol %. This decrease can be accounted for by considering that this substrate was in the form of premicelles or micelles at  $5.0 \times 10^{-5} M$ , the conditions of the measurement.

**Hydrolysis of  $\text{S}_n^-$  Catalyzed by Poly[4(5)-vinylimidazole] (PVIm).** Previous results for the hydrolysis of  $\text{S}_{12}^-$  indicated that apolar influences in the PVIm catalyzed reaction could lead to large rate enhancements in comparison to the Im catalyzed case.<sup>1</sup> These forces were found to dramatically increase when the water content of the solvent was increased. The PVIm

catalyzed reaction was reported to be a strict second-order process for  $\text{S}_{12}^-$  in 60 vol % ethanol, but had a different kinetic pattern in the low alcohol composition solvents where apolar forces become significant.<sup>2</sup> It was found that the results indicated saturation and thus could be treated according to the Michaelis–Menten mechanism.<sup>15</sup> Although certain PVIm systems in this study also showed a deviation from strict second-order kinetics and even deviated under pseudo-first-order conditions, a  $k_{\text{cat}}$  value was calculated and is reported as an “apparent” second-order rate constant (see Tables II and III). This was done as a means of quantifying the data in order to probe the nature of the forces operating in these particular systems. It must be borne in mind that the  $k_{\text{cat}}$  values for certain of the PVIm catalyzed cases are very dependent on the PVIm/ $\text{S}_n^-$  ratio. In the accompanying paper<sup>16</sup> we offer evidence suggesting that a long-lived, acylated-PVIm intermediate is responsible for an accelerative pseudo-first-order kinetic behavior. Tables II and III report several more examples of this interesting accelerative kinetic pattern; the accompanying paper details additional evidence explaining the cause of this acceleration.

One of the most striking observations of the data accumulated in Tables II and III is that the order of reactivity based on steric factors which was observed in the Im catalysis of  $\text{S}_n^-$  is no longer present with PVIm in solvent media with a low alcohol content. For example, in 20 vol % 1-propanol–water, the apparent second-order rate constants increase with increasing chain length of the substrate from 2 to 18 carbons. The same trend is observed in 25 vol % ethanol–water.

The effect of decreasing alcohol composition on the PVIm catalyzed hydrolyses is most dramatic considering the  $\text{S}_{12}^-$  substrate in both ethanol and 1-propanol solvent systems. Greater than  $10^3$ -fold rate increases were observed upon lowering the ethanol content from 60 to 20 vol % or the 1-propanol content from 40 to 15 vol %. The increasing polarity of the solvent can only explain a small fraction of the rate increase.

The large increases in rate and the change in order of reactivity for the PVIm catalyzed cases upon lowering the alcohol content of the solvent are reflected in the  $r$  values. The  $r$  value (i.e., rate enhancement) is defined as  $k_{\text{cat}}$  for PVIm/ $k_{\text{cat}}$  for Im, for a particular substrate.

In all cases investigated the  $r$  values were greater than one.

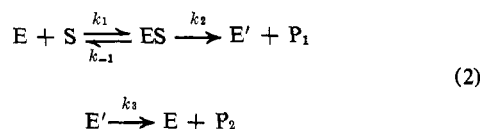
**Deviations from Pseudo-First-Order Kinetics.** There is convincing evidence for the formation of a catalyst–substrate complex in enzyme systems<sup>12</sup> and some synthetic catalysts appear to operate by a similar mechanism.<sup>1,3,4,6</sup> This complexation is reflected by the observation of “saturation” kinetics. Complexation is described by eq 1 and is in turn derived from the mechanism of eq 2 when the deacylation step ( $k_3[E']$ ) is negligible.

$$v = \frac{k_2[\text{S}]_0[\text{E}]_0}{[\text{S}]_0 + K_m} \quad (1)$$

(15) M. Morimoto, Ph.D. Thesis, The University of Michigan, 1969.

(16) C. G. Overberger and R. C. Glowaky, *J. Amer. Chem. Soc.*, **95**, 6014 (1973).

where  $[S]_0 \gg [E]_0$  and  $K_m = (k_{-1} + k_2)/[S]_1$ .



However, it is conceivable that the saturation-like behavior observed could be due to a build up of acylated intermediate,  $E'$ , if the acylation reaction is fast with respect to the determination of the initial rate. Saturation-like behavior has been attributed to a mechanism in which the rate of hydrolysis of an ester shows a leveling effect due to the "covalent saturation" of the imidazole sites with acyl groups.<sup>17</sup>

Substrates  $S_7^-$  and  $S_{12}^-$  were subjected to a kinetic study in 1-propanol-water using a large excess of substrate with respect to catalyst (see Figure 1). Kinetic descriptions indicative of saturation were observed for  $S_7^-$  in 15 and 20 vol % 1-propanol-water; the  $k_2$  and  $K_m$  values obtained were  $0.74 \text{ min}^{-1}$  and  $3.94 \times 10^{-4} \text{ M}$ , respectively, in 20% and  $0.94 \text{ min}^{-1}$  and  $3.14 \times 10^{-4} \text{ M}$ , respectively, in 15%. In all other cases ( $S_{12}^-$  and  $S_7^-$  in 10%) no saturation kinetics could be observed. Instead, a bell-shaped profile was observed, in the velocity *vs.* concentration of substrate plot with the maximum being very near the cmc of the substrate. Thus, a sufficient excess of substrate to demonstrate saturation could not be used meaningfully. When using an excess of catalyst instead of an excess of substrate, the initial rate of hydrolysis should obey eq 3. The kinetic parameters  $k_2$  and  $K_m$  con-

$$v = \frac{k_2[S]_0[E]_0}{[E]_0 + K_m} \quad (3)$$

$[E]_0 > [S]_0$

ceptually should have the same values under the two sets of conditions.

Because of the low solubility of PVIm in 15 vol % 1-propanol-water, it was impossible to reach a sufficient excess of catalyst, and this study was thus only carried out in 20 vol %. As shown in Figure 2, saturation kinetics were obtained for  $S_2^-$ ,  $S_7^-$ , and  $S_{12}^-$ . However, no increase of the turnover number,  $k_2$ , was observed when the chain length of the substrate was increased (see Table IV).

**Table IV.** Influence of Catalyst Concentration on the Initial Esterolysis Rate<sup>a</sup>

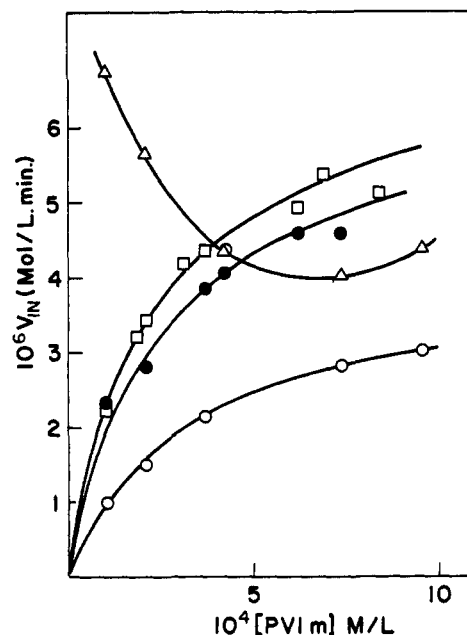
$S_n^-$	$k_2$ , $\text{min}^{-1}$ <sup>b</sup>	$10^4 K_m$ , mol
$S_2^-$	0.15	2.96
$S_7^-$	0.15	2.86
$S_{12}^-$	0.086	4.04

<sup>a</sup> pH = 8.00,  $\mu = 0.02$ ,  $T = 26^\circ$ ; 20 vol % 1-propanol-water.

<sup>b</sup> The observed value has been corrected for protonated imidazole residues ( $\alpha_1 = 0.94$ ).

The behavior of  $S_{18}^-$  in the presence of excess PVIm was completely different from the three other substrates: the initial rate *decreased* when the polymer concentration was increased! A similar situation was observed when studying the influence of PVIm concentration

(17) Y. Okamoto and C. G. Overberger, *J. Polym. Sci., Part A-1*, **10**, 3387 (1972).



**Figure 2.** PVIm catalyzed initial esterolysis rates of  $S_2^-$  (○),  $S_7^-$  (●),  $S_{12}^-$  (□), and  $S_{18}^-$  (△) in 20 vol % 1-propanol-water;  $[S_n^-] = 5.0 \times 10^{-5} \text{ M}$ ,  $\mu = 0.02$ ,  $[\text{Tris}] = 0.02 \text{ M}$ , pH 8.0,  $26^\circ$ .

on  $k_{\text{cat}}$  in 30 vol % 1-propanol-water and is discussed in the accompanying paper.<sup>16</sup>

### Effect of pH

Previously we reported that based on the pH-rate profile for  $S_{12}^-$  *vs.*  $S_2^-$ , the electrostatic contribution to the complexation was negligible.<sup>1</sup> Additional information concerning the apolar role in the catalytic process can be obtained by observing the effect of protonation of the polymer on the  $r$  values for the four substrates under investigation in the present study.

A variation of the pH of a PVIm solution produces a change in the number of protonated imidazole residues in the polymer, accompanied by a shrinkage or expansion of the macromolecule.<sup>18</sup> Further, a variation in the extent of protonation of PVIm should effect the rate of hydrolysis of  $S_n^-$ . Unfortunately, PVIm proved to be poorly soluble at pH 8.8, so that our study was restricted to pH 8.03 and 7.05 (Table V).

**Table V.** Influence of pH on the Esterolysis of Long Aliphatic Chain Substrates

Substrate	$k_{\text{cat}}/\alpha_1$ , 1/(mol min)					
	pH 7.05			pH 8.03		
	Im	PVIm	$r^b$	Im	PVIm	$r$
$S_2^-$	21.7	92.3	4.25	17.3	59.5	3.4
$S_7^-$	2.82	25.7	9.1	4.84	19.7	4.1
$S_{12}^-$	2.93	29.45	10.0	4.69	17.7	3.8
$S_{18}^-$	3.06	340	111	4.69	276 <sup>c</sup>	59

<sup>a</sup> Solvent: 30 vol % 1-propanol-water,  $\mu = 0.02$ ,  $T = 26^\circ$ ,  $[\text{Im}] = [\text{PVIm}] = 5 \times 10^{-4} \text{ M}$ ,  $[S] = 5 \times 10^{-5} \text{ M}$ . <sup>b</sup> See Table III.

Decreasing the pH of the reaction medium from 8.03 to 7.05 produced an increase in the  $r$  values for all

(18) For a discussion of the properties of polyelectrolyte solutions, see C. Tanford, "Physical Chemistry of Macromolecules in Solution," Wiley, New York, N. Y., 1961; H. Morawetz, "Macromolecules in Solution," Wiley-Interscience, New York, N. Y., 1965.

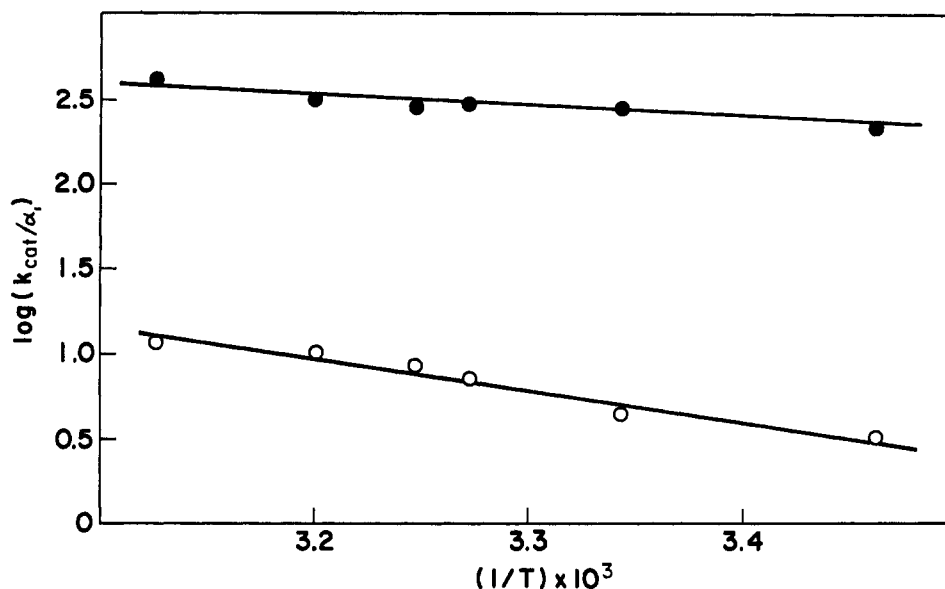


Figure 3. Temperature dependence of PVIm catalyzed (●) and Im catalyzed (○) esterolyses of  $S_{18}^-$  in 30 vol % 1-propanol-water.

four substrates. This increase was most pronounced for  $S_7^-$  and  $S_{12}^-$  and can be related to a reduction of steric hindrance in the more protonated, and thus more extended polymer coil. This process favors the bulkier substrates over the relatively small  $S_2^-$ . The increase in  $r$  value for  $S_{18}^-$  was smaller than for the two intermediate chain length substrates; the hydrolysis in the  $S_{18}^-$  case is somewhat different demonstrating an accelerative behavior. This might indicate that steric effects are less important at pH 8.03 when there are significant apolar effects.

**Temperature Dependence.** Hydrophobic (apolar) and lyophobic interactions are known to be temperature dependent;<sup>19</sup> the former are mainly entropy driven while the latter are mainly enthalpy driven. On the other hand, the dimensional structure of macromolecules is also temperature dependent. The catalyzed esterolysis reaction of  $S_{18}^-$  in 30 vol % 1-propanol-water was thus subjected to a temperature variation study.

Figure 3 shows that both the Im and PVIm catalyzed reactions showed fairly linear Arrhenius plots. The kinetic results were corrected for the pH variation of the solutions and the  $pK$  variation of the catalysts with temperature. The activation parameters listed in Table VI show a strong reduction in the activation

is also reduced by 8.8 eu. These results compare fairly well with those previously obtained for the esterolysis of *p*-nitrophenyl acetate (PNPA),<sup>20</sup> except that the magnitude of the differences between polymeric and monomeric reactions is larger in the  $S_{18}^-$  case.

The larger difference in activation energy and entropy of the PVIm and Im catalyzed esterolyses of  $S_{18}^-$ , when compared with PNPA as a substrate, is attributable to an eased formation of the activated complex by apolar attraction between the reactants as well as to a higher degree of order in the polymeric activated complex.

## Experimental Section

**Poly[4(5)-vinylimidazole] (PVIm).** A solution of 4(5)-vinylimidazole<sup>21</sup> (2.0 g, 0.021 mol) and 2,2'-azobis(2-methylpropionitrile) (4 mg, 0.11 mol %) in 20 ml of dried benzene was degassed *via* several freeze-thaw cycles and sealed in a glass tube while under vacuum. The tube was heated for 65 hr at 65° and the precipitated polymer (1.83 g, 91% yield) isolated. The polymer was purified by two reprecipitations from methanol-benzene and one from methanol-acetone. The resultant white sample was dried at 100° over  $P_2O_5$  for 4 days and showed a single absorption in the uv at 214 m $\mu$  (MeOH,  $\epsilon$  3900),  $\eta_{sp} = 0.44$  (at 0.5 g/dl, MeOH, 25.0°).

*Anal.* Calcd for  $C_5H_6N_2$ : C, 63.81; H, 6.43; N, 29.75. Found: C, 63.76; H, 6.72; N, 28.69.

**3-Nitro-4-acetoxybenzoic Acid ( $S_2^-$ ).** This compound was prepared according to the procedure of Overberger, *et al.*,<sup>22</sup> mp 152° (lit.<sup>22</sup> mp 152°).

**3-Nitro-4-heptanoyloxybenzoic Acid ( $S_7^-$ ).** 3-Nitro-4-hydroxybenzoic acid (18.3 g, 0.06 mol) and heptanoic anhydride (50 g, 0.21 mol) were combined and heated to 60° with stirring. Then 5 drops of concentrated sulfuric acid was added and the dark mixture stirred for 15 min, poured into 250 ml of cyclohexane, treated with Norit, and filtered. Upon cooling the mixture to 5° for 36 hr the ester crystallizes. The product was isolated and a second crop obtained from the mother liquor. Recrystallization from cyclohexane-aqueous ethanol (1:1 v/v), then cyclohexane again gave a pure product, softening point 70–71°, mp 75°.

*Anal.* Calcd for  $C_{14}H_{17}NO_6$ : C, 56.95; H, 5.76; N, 4.75. Found: C, 57.01; H, 5.67; N, 4.64.

Table VI. Activation Parameters for the Esterolysis of  $S_{18}^-$  in 30 Vol % 1-Propanol<sup>a</sup>

	$E^\ddagger$	$H^\ddagger$	$F^\ddagger$	$S^\ddagger$
Imidazole	8.3	7.7	19.5	-39.6
Poly[4(5)-vinylimidazole] <sup>b</sup>	2.7	2.1	16.7	-48.4

<sup>a</sup> All values are in kcal/mol except  $S^\ddagger$  (eu). Reaction conditions were  $\mu = 0.02$ , pH 7.70–8.16,  $[S] = 5 \times 10^{-5}$  M,  $[Cat] = 5 \times 10^{-4}$  M. <sup>b</sup> The activation parameters correspond to the first-order portion of the kinetics.

energy for the polymeric reaction relative to the monomeric reaction ( $\Delta\Delta E^\ddagger = 5.6$  kcal); the activation entropy

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(20) C. G. Overberger, T. St. Pierre, C. Yaroslavsky, and S. Yaroslavsky, *J. Amer. Chem. Soc.*, **88**, 1184 (1966).

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(22) C. G. Overberger, T. St. Pierre, N. Vorchheimer, J. Lee, and S. Yaroslavsky, *J. Amer. Chem. Soc.*, **87**, 296 (1965).

**3-Nitro-4-dodecanoyloxybenzoic Acid ( $S_{12}^-$ ).** Dodecanoyl (lauroyl) chloride (10.93 g, 0.05 mol in 50 ml of ethyl ether) was added slowly to a stirred solution of 3-nitro-4-hydroxybenzoic acid (9.15 g, 0.05 mol) and triethylamine (5.05 g, 0.05 mol) in 250 ml of ethyl ether. After the addition, the milky solution was stirred at room temperature for 3 hr. The precipitated triethylamine hydrochloride was filtered off and the filtrate evaporated to dryness by means of a rotary evaporator under reduced pressure. The crude product could be purified by two successive recrystallizations from cyclohexane then methanol, softening point 81°, mp 100° (lit.<sup>1</sup> mp 82°).

**3-Nitro-4-octadecanoyloxybenzoic Acid ( $S_{18}^-$ ).** Octadecanoyl (stearoyl) chloride (30.25 g, 0.10 mol) was added dropwise to a stirred solution of 3-nitro-4-hydroxybenzoic acid (18.30 g, 0.10 mol) and triethylamine (10.10 g, 0.11 mol) in 250 ml of dioxane. The stirring was continued for 16 hr; then the flask was heated to 60° for 1 hr. The milky solution was cooled and filtered to remove triethylamine hydrochloride and the filtrate evaporated under reduced pressure by rotary evaporation. The crude product could be purified by successive recrystallizations from heptane and methanol.

*Anal.* Calcd for  $C_{23}H_{35}NO_6$ : C, 66.81; H, 8.69; N, 3.12. Found: C, 66.88; H, 8.69; N, 3.12.

**Determination of  $pK_a$ .** The sample (PVI<sub>m</sub> or Im) was dissolved in the appropriate solvent containing  $2.0 \times 10^{-2}$  N HCl. This solution was then transferred to a thermostated cell and titrated with 1 N NaOH using a micropipet. The pH change with added base was followed on a Radiometer titlt. The blank titration curves were obtained by titrating the appropriate solutions with no sample present. The glass electrode response was checked against Beckman standard buffers (pH 4 and 10) before each determination.

The differences in the added amounts of NaOH at various pH's between blank and sample titration curves were determined. A differential titration curve was obtained and the  $pK_1$  determined at the half-neutralization point. This was done by a plot of pH *vs.*  $\log \alpha_1/(1 - \alpha_1)$  from the modified Henderson-Hasselbalch equation<sup>23</sup> (4). Such plots were found to be linear in the range of 0.1 <

$$pH = pK + n \log [\alpha_1/(1 - \alpha_1)] \quad (4)$$

$\alpha_1 < 0.9$ . Table VII summarizes the  $pK_1$  values obtained; all

**Table VII.** Potentiometric Titrations of PVI<sub>m</sub> and Im in Alcohol-Water Mixture,  $\mu \sim 0.02$

Alcohol	Vol % alco- hol- water	Temp, °C	—PVI <sub>m</sub> — $pK_1$ $r$		Im $pK_1$
1-PrOH	40	26	5.34	2.38	6.55
1-PrOH	30	26	5.23	2.70	6.64
1-PrOH	30	35	5.05	2.70	6.60
1-PrOH	30	44	4.91	2.66	6.54
1-PrOH	25	26	5.31	2.43	6.80
1-PrOH	20	26	5.17	2.40	6.87
1-PrOH	15	26	5.15	2.65	6.92
1-PrOH	10	26	5.30	3.14	7.02
EtOH	20	26	5.77	2.05	6.90
EtOH	25	26	5.77	2.13	6.86
EtOH	33	26	5.50	2.19	6.79
EtOH	40	26	5.53	2.23	6.68
EtOH	60	26	5.98	2.09	6.51

(23) A. Katchalski, N. Shavit, and H. Eisenberg, *J. Polym. Sci.*, **13**, 69 (1954).

kinetic data were corrected for the fraction of neutral, catalytically active imidazole present ( $\alpha_1$ ).

**Determination of the Critical Micelle Concentration.** The absorbance of pinacryanol chloride<sup>10,11</sup> (Eastman Organic Chemicals) ( $4.0 \times 10^{-6}$  M) was followed at 610 m $\mu$  as a function of increasing concentration of  $S_7^-$ ,  $S_{12}^-$ , or  $S_{18}^-$  in 20, 30, and 40 vol % ethanol-water. The final solutions had pH 8,  $\mu = 0.02$ , [Tris] = 0.02 M, and 26°; *i.e.*, the same conditions as employed in the kinetic studies. The cmc values were estimated graphically and correspond to the minimum in the plot of absorbance *vs.* concentration of  $S_n^-$ . A spectrophotometer was in fact unnecessary for the cmc determination; above the cmc the solutions are a bright blue, while below it they are a light shade of pink.

The buffered dye solutions were found to fade 10–20% at 610 m $\mu$  after *ca.* 24 hr in the light. Thus, the dye is best prepared in an appropriate ethanol-water solvent or absolute ethanol and then mixed with a second buffered ethanol-water solution just prior to use. The substrates were dissolved in absolute ethanol and added to the freshly prepared, buffered dye solution. The absorbance of the solution was measured at a specified period of time (*ca.* 15 min in this study) after adding the substrate. Scattered absorbance readings were obtained if the sample was allowed to stand for a prolonged period, due to settling of the dye-substrate salt suspension and fading of the dye.

**Measurement of Hydrolysis Rates ( $k_{\text{obsd}}$ ).** **1. Slow Reactions.** The procedure used was essentially the same as previously described.<sup>1,22</sup> To 3.0 ml of the appropriate catalyst solution in a 1-cm cuvette was added 200  $\mu$ l of substrate in absolute ethanol (or 1-propanol). Typically, the final solutions had the following solution properties: pH 8.0,  $\mu = 0.02$ , [tris(hydroxymethylamino-methane)] (Tris) = 0.02 M, 26°. The alcohol composition and concentrations of catalyst and substrate reported are those of the final 3.2-ml solutions. After mixing the added substrate by inverting the cuvette several times, the appearance of 3-nitro-4-hydroxybenzoic acid was monitored as a function of time at 400 m $\mu$  on a Beckman DU-2 spectrophotometer. All the data were obtained, unless otherwise noted, under conditions in which [catalyst]  $\gg$  [substrate], and were treated as first-order kinetics by plotting  $\ln (OD_\infty - OD_t)$  *vs.* time. The slope of this line was taken as the pseudo-first-order rate constant ( $k_{\text{measd}}$ ). For the cases showing an accelerative behavior,  $k_{\text{measd}}$  was determined from the slope at *ca.* 75% reaction. The following expressions were used to calculate  $k_{\text{obsd}}$  and  $k_{\text{cat}}$ .  $k_{\text{obsd}} = k_{\text{measd}} - k_{\text{bl}}$  and  $k_{\text{cat}} = k_{\text{obsd}}/[\text{cat}]$ . All  $k_{\text{cat}}$  values reported are corrected for the fraction of neutral, catalytically active imidazole.

**2. Fast Reactions.** All reactions which had a half-life of less than 2 min were followed on a Durrum-Gibbs stopped-flow spectrophotometer. The data were obtained as an oscilloscope tracing of % *T* *vs.* time; this tracing was photographed for a permanent record. The % *T* was read off the photographs at certain time intervals, then converted into OD. The data so obtained were treated as pseudo-first-order kinetics by plotting  $\ln (OD_\infty - OD_t)$  *vs.* time. The  $k_{\text{cat}}$  value was determined as described above.

**3. Initial rates** were determined from plots of optical density *vs.* time on either the Beckmann DU-2 or Durrum-Gibbs stop-flow spectrophotometer, depending on the speed of the reaction. Calculations of initial rate values, *v*, were made from

$$v = [(OD_1 - OD_2)/(t_1 - t_2)]/\epsilon \quad (5)$$

where  $\epsilon$  is the extinction coefficient of the substrate being used.

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