

# Decarboxylation of 6-Nitrobenzisoxazole-3-carboxylate Catalyzed by Ammonium Bilayer Membranes. A Comparison of the Catalytic Behavior of Micelles, Bilayer Membranes, and Other Aqueous Aggregates

Toyoki Kunitake,\*<sup>1</sup> Yoshio Okahata, Reiko Ando, Seiji Shinkai, and Shin-ichi Hirakawa

Contribution No. 580 from the Department of Organic Synthesis, Faculty of Engineering, Kyushu University, Fukuoka 812, Japan. Received May 27, 1980

**Abstract:** Decarboxylation of 6-nitrobenzisoxazole-3-carboxylate was studied at 5–50 °C in water in the presence of CTAB micelles, dialkylammonium ( $2C_nN^+2C_1$ ) bilayer membranes, and trioctylmethylammonium (TMAC) aggregates. These aqueous aggregates possess totally different morphologies with each other, but their general rate acceleration effects increased simply with increasing local hydrophobicities: CTAB <  $2C_nN^+2C_1$  < TMAC. In contrast with the other systems, the rate enhancement by the dialkylammonium membrane was influenced by its hydrophobicity and fluidity. The crystal-to-liquid crystal phase transition determines the membrane fluidity. The Arrhenius plots for the membrane catalysis of  $2C_nN^+2C_1$  ( $n = 12, 14, 16, 18$ ) invariably showed inflections at or near the respective phase transition temperature ( $T_c$ ). The activation energy data suggest that the membrane catalysis is governed mainly by the hydrophobicity and fluidity (or rather rigidity) at temperatures above and below  $T_c$ , respectively.

It is established through our systematic studies<sup>2</sup> that the stable bilayer membrane is formed from a variety of amphiphiles which contain two higher alkyl chains ( $C_{10}$ – $C_{20}$ ). The physicochemical property of these bilayers is similar to that of the bilipid bilayer in many respects.<sup>3</sup> For instance, the molecular movement is rather restricted in the bilayer phase, and in the case of the ammonium bilayer, the presence of the crystal–liquid crystal phase transition was confirmed by diverse techniques such as differential scanning calorimetry,<sup>4</sup> NMR spectroscopy,<sup>5</sup> fluorescence polarization,<sup>5,6</sup> positron annihilation.<sup>6</sup> Thus, the ammonium bilayer aggregate provides unique microenvironments of reactions which have hitherto not been available.

Alkylammonium salts possess quite different aggregation behavior, depending on whether the number of long-chain alkyl substituents is one (conventional micelle), two (bilayer membrane) or three (small aggregates).<sup>6</sup> It is of considerable interest to compare the characteristics of these ammonium aggregates as the microenvironment of reaction. The catalytic property of these ammonium aggregates has been compared in these laboratories in the case of the ester hydrolysis<sup>8</sup> and the proton abstraction<sup>9</sup> by anionic reagents, and some anomalous effects due to the bilayer structure were observed. However, the discussion on the membrane catalysis was not necessarily straightforward.

Unimolecular reactions would be better probes of the environmental effect than the bimolecular reaction, since one need not take the proximity term into account (see eq 1). The de-

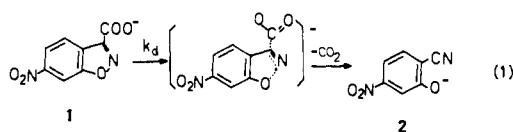
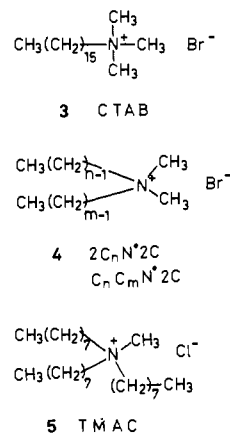


Chart I

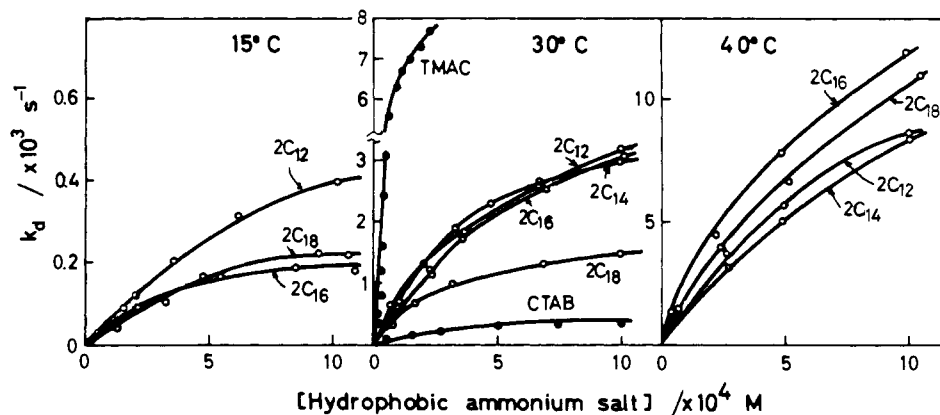


carboxylation of carboxylic acids meets this requirement, for it is unimolecular and almost free from acid and base catalyses and the rate constants are extremely solvent dependent.<sup>10</sup> We selected 6-nitrobenzisoxazole-3-carboxylate **1** as the substrate, since this is one of the most extensively investigated compounds in relation to the medium effect. The decarboxylation rate is smallest in water and is enhanced in aprotic solvents.<sup>11–13</sup> Conventional cationic micelles<sup>14–16</sup> and cationic polymers with hydrophobic side chains (polysoaps)<sup>17,18</sup> are also effective catalysts, along with polymeric crown ethers.<sup>19</sup>

In this article, we compare the decarboxylation rate of **1** in the presence of aqueous aggregates of single-chain (**3**), double-chain (**4**), and triple-chain (**5**) ammonium amphiphiles. The peculiar catalytic property of the ammonium bilayer membrane is of particular interest.

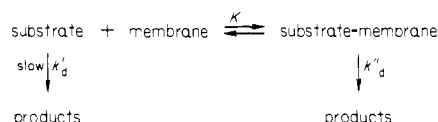
(1) To whom correspondence should be addressed.  
 (2) For a short review see: Kunitake, T. *J. Macromol. Sci., Chem.* **1979**, *A13*, 587–602.  
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**Figure 1.** Decarboxylation rate as a function of the concentration of alkylammonium salts: pH 9.1, 0.02 M borate buffer,  $\mu = 0.016$  (KCl), [substrate] =  $7.7 \times 10^{-5}$  M.

#### Scheme I



#### Experimental Section

**Materials.** 6-Nitrobenzisoxazole-3-carboxylic acid was prepared according to the method of Borsche<sup>20</sup> and recrystallized from methanol, mp 167–169 °C (lit.<sup>20</sup> 167–169 °C (monohydrate)). Commercial hexadecylmethylammonium bromide (CTAB) was recrystallized two times from water, and its purity was confirmed by the surface tension measurement.<sup>21</sup> Commercial triethylmethylammonium chloride (5, TMAC) (Dojin Chemicals Co.) was used without further purification. Dialkyldimethylammonium bromides (4,  $2C_nN^+2C_1$ ,  $C_nC_mN^+2C_1$ ) were prepared by reaction of *N,N*-dimethylalkylamines and alkyl bromides in refluxing ethanol and purified by repeated recrystallization from ethyl acetate.<sup>22</sup> The products were identified by NMR spectroscopy, thin-layer chromatography (with flame ionization detector, Iatron Laboratories, Model TFG-10), and elemental analysis.

**Rate Measurement.** The stock solution of the substrate was prepared on the day of use. Dialkyldimethylammonium bromides were suspended in 0.02 M borate buffers (pH 9.1,  $\mu = 0.016$  with KCl) and sonicated for 2–5 min by using a Branson Sonifier 185 (sonic power 40). Clear solutions ( $10^{-4}$ – $10^{-3}$  M) were thus obtained. The progress of the reaction was followed at 410 nm by using Hitachi UV-visible spectrophotometers (Models 124 and 200) equipped with thermostated cell holders. The rate constant ( $k_d$ ) was calculated from the first-order plot of up to 3 half-lives.

**Other Measurements.** The phase transition temperature was determined for aqueous solutions (1.0 wt %, ca. 0.02 M) of dialkylammonium salts by using a differential scanning calorimeter: Daini-Seikosha, Model SSC 560. The temperature was raised from 0 to 100 °C at a rate of 2 °C/min. The critical micelle (aggregate) concentration of dialkylammonium salts was estimated by the dye (2,6-dichlorophenolindophenol) method.<sup>7</sup> The surface tension method was difficult to apply to the cmc determination because of the irreproducible surface property of these solutions. The aggregate weight was determined by the laser light scattering method.<sup>23</sup>

#### Results

Figure 1 shows the relation of  $k_d$  and the concentration of ammonium salts at 15, 30, and 40 °C. The substrate concentration was usually  $7.7 \times 10^{-5}$  M. The rate constant increased gradually with the increase in the ammonium concentration and tended to level off at the later stage. Similar types of the kinetic behavior have been observed in the micellar and polysoap catalysis. As in the other systems, the data of Figure 1 may be analyzed by the saturation kinetics of Scheme I, where  $K$  is the association constant of substrate with membrane (or other aggregates),  $k'_d$

is the decarboxylation rate constant without membrane, and  $k_d''$  is that for the membrane-bound species.

Equation 2 has been derived for [membrane]  $\gg$  [substrate],<sup>24</sup> where  $q = (k_d''/k_d) - 1$ .

$$k_d'/(k_d - k_d') = 1/qK[\text{membrane}] + 1/q \quad (2)$$

When eq 2 was applied to the data of Figure 1, the satisfactory correlation ( $r > 0.99$ ) was not found in many cases. It appears that very smooth saturation can not be observed in the case of rigid bilayers (see below). In addition, because of the limited solubility, the TMAC concentration could not be increased beyond that recorded in Figure 1, and this prevented the use of eq 2 for the TMAC data. Therefore, in the following is discussed the rate augmentation only in terms of  $k_d$ , although the value of  $K$  lies in the range of 1500–3000 M<sup>-1</sup>, which is close to those of cationic micelles and polysoaps.

The catalytic efficiency was in the following order at 30 °C: TMAC >  $2C_nN^+2C_1$  > CTAB. The rate augmentation relative to the spontaneous rate ( $k_d = 6.0 \times 10^{-6}$  s<sup>-1</sup>) at 30 °C was 1300-fold at [TMAC] =  $2 \times 10^{-4}$  M, 500-fold at [ $2C_{12}N^+2C_1$ ] =  $1 \times 10^{-3}$  M, and 50-fold at [CTAB] =  $2 \times 10^{-3}$  M. All of the ammonium salts form aggregates in the concentration range of Figure 1.

At 30 °C,  $2C_{18}N^+2C_1$  was least effective among the double-chain ammonium salts. The decarboxylation has been known to be accelerated in the hydrophobic microenvironment. Then  $2C_{18}N^+2C_1$  should give larger rate augmentation than other dialkylammoniums. That this is not the case suggests that the rate acceleration is related to the peculiar property of the ammonium bilayer. In fact, the relative rate acceleration changes with the reaction temperature, as also shown in Figure 1:  $2C_{12}N^+2C_1 > 2C_{18}N^+2C_1 > 2C_{16}N^+2C_1$  at 15 °C;  $2C_{16}N^+2C_1 > 2C_{18}N^+2C_1 > 2C_{12}N^+2C_1 > 2C_{14}N^+2C_1$  at 40 °C.

The phase transition temperature ( $T_c$ ) of a dilute solution of the dialkylammonium bilayer was determined by differential scanning calorimetry as follows:  $45 \pm 1$  °C for  $2C_{18}N^+2C_1$ ,  $28 \pm 1$  °C for  $2C_{16}N^+2C_1$  and  $16 \pm 1$  °C for  $2C_{14}N^+2C_1$ . A DSC peak could not be detected for  $2C_{12}N^+2C_1$ .<sup>25</sup> These  $T_c$  values indicate that the  $2C_{18}N^+2C_1$  bilayer is in the rigid state at all the reaction temperatures and that the  $2C_{12}N^+2C_1$  bilayer is in the fluid (liquid crystalline) state. Then the relative inefficiency of  $2C_{18}N^+2C_1$  bilayer at 15 and 30 °C is attributable to the membrane rigidity. The rate acceleration by the  $2C_{16}N^+2C_1$  bilayer

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(25) It was recently found in these laboratories that  $T_c$  of the dialkylammonium bilayer varied with the pretreatment procedure of the aqueous sample. Thus,  $T_c$  of aqueous  $2C_{12}N^+2C_1$  was  $14 \pm 2$  °C when the heating cycle of the DSC measurement was started from  $-50$  °C, but  $T_c$  could not be detected when the heating was started from 0 °C. The  $T_c$  values given in the text correspond to the latter one since this reflects more faithfully the state of dispersion of the aqueous bilayer in the decarboxylation experiment: unpublished results in these laboratories. The  $T_c$  data previously given in the literature<sup>4,26</sup> belong to the former values.

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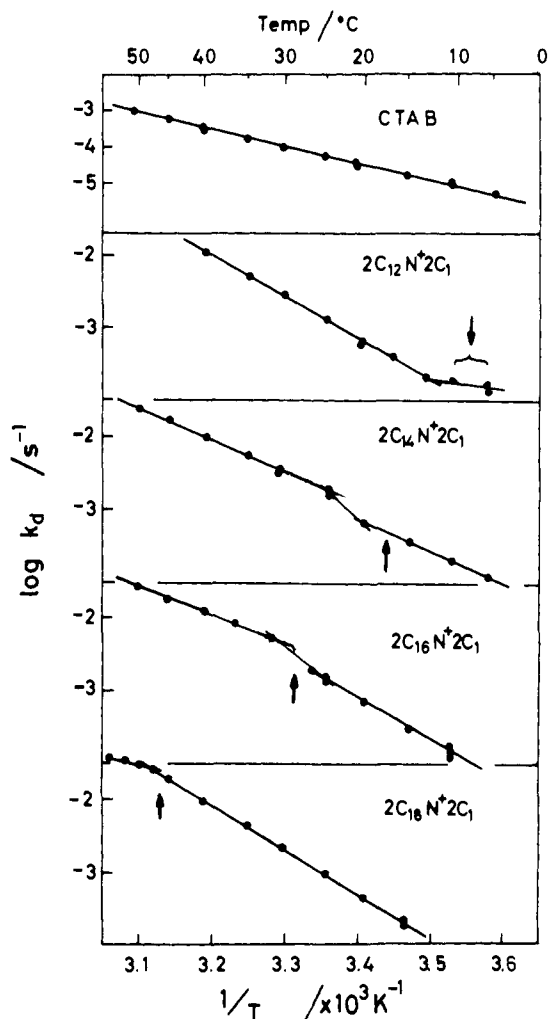


Figure 2. Arrhenius plots of the catalytic decarboxylation by  $2C_nN^+2C_1$  bilayers: pH 9.1, 0.02 M borate buffer,  $\mu = 0.016$  (KCl), [ammonium salt] =  $1 \times 10^{-3}$  M, [substrate] =  $1 \times 10^{-4}$  M.

( $T_c = 28$  °C) is inefficient at 15 °C but is relatively efficient at 30 and 40 °C.

In order to make the influence of the phase transition more apparent, we examined the catalytic decarboxylation over the temperature range of 0–50 °C at a fixed ammonium concentration of  $1 \times 10^{-3}$  M and the Arrhenius plots are obtained as shown in Figure 2. The Arrhenius plots for CTAB give a straight line, but those for the dialkylammonium bilayers invariably have breaks. These breaks are present at temperatures close to  $T_c$  which is indicated in the figure by the arrow for the respective bilayer. The inflection point (or range) corresponds almost exactly to  $T_c$  in the case of the  $2C_{18}N^+2C_1$  and  $2C_{16}N^+2C_1$  bilayers. But the inflection range for the  $2C_{14}N^+2C_1$  bilayer is higher than  $T_c$  by 5–10 °C. The break is also found at 12–13 °C for the  $2C_{12}N^+2C_1$  bilayer which did not show a DSC peak.  $T_c$  is estimated to be 5–10 °C for the aqueous  $2C_{12}N^+2C_1$  bilayer from the data for other dialkylammonium bilayers. Then the inflection point is a little higher than the estimated  $T_c$ .

Figure 3 summarizes the rate acceleration effect at 30 °C of the  $C_{18}C_mN^+2C_1$  bilayers in which  $m = 8, 10, 12, 14,$  and 16. The decarboxylation rate increases with the increase in the ammonium concentration. The catalytic effect of  $C_{18}C_mN^+2C_1$  is similar for  $m = 10, 12, 14,$  and 16, but that of  $C_{18}C_8N^+2C_1$  is much smaller. It was shown previously that stable bilayer membranes were always formed from  $C_{18}C_mN^+2C_1$  if  $m \geq 10$ .<sup>22</sup> The bilayer formation could not be seen for  $C_{18}C_8N^+2C_1$  by electron microscopy. The NMR experiment was consistent with these results in that the molecular fluidity of the  $C_{18}C_8N^+2C_1$  aggregate was close to that of the conventional globular micelle (CTAB).<sup>5</sup>

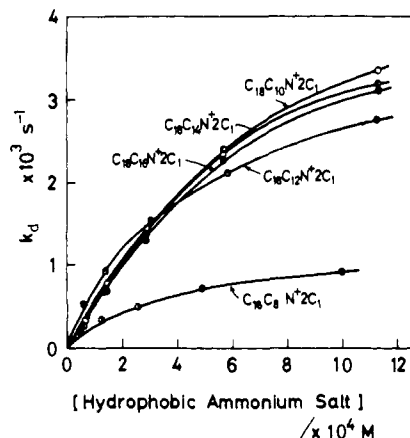


Figure 3. Decarboxylation rate as a function of the concentration of  $C_{18}C_mN^+2C_1$  bilayers: 30 °C, pH 9.1, 0.02 M borate buffer,  $\mu = 0.016$  (KCl), [substrate] =  $7.7 \times 10^{-5}$  M.

The maximal rate acceleration of  $C_{18}C_8N^+2C_1$  is ca. 100-fold which lies between 500-fold of  $C_{18}C_mN^+2C_1$  ( $m \geq 10$ ) and 50-fold of CTAB.

The rate augmentation by  $C_{18}C_mN^+2C_1$  ( $m \geq 10$ ) is larger than that by  $2C_{18}N^+2C_1$ . This difference is again explained by the membrane fluidity. The  $T_c$  value was 31 and 21 °C for the  $C_{18}C_{16}N^+2C_1$  and  $C_{18}C_{14}N^+2C_1$  bilayers, respectively, but the phase transition was not detected for the  $C_{18}C_{12}N^+2C_1$ ,  $C_{18}C_{10}N^+2C_1$ , and  $C_{18}C_8N^+2C_1$  bilayers.<sup>25</sup> The reaction temperature of Figure 3 is 30 °C, and the bilayer-forming  $C_{18}C_mN^+2C_1$ 's ( $m = 10, 12, 14,$  and 16) are all fluid at this temperature. The  $2C_{18}N^+2C_1$  bilayer ( $T_c = 45$  °C) is still rigid at this temperature and gives smaller rate enhancements.

Figure 4 illustrates the influence of added salts and cholesterol on the rate acceleration of  $2C_{12}N^+2C_1$  bilayer and CTAB micelle. The influences are contrasting between these two aggregates. Addition of KCl produced maximal acceleration at 0.1–0.2 M in the case of the bilayer membrane but a shallow minimum was observed for the CTAB micelle. Addition of sodium benzoate (organic anion) and cholesterol in the bilayer system led to gradual decreases in the rate augmentation, but the reverse was true for the micelle.

Similar experiments were not easy to carry out for the TMAC aggregate, because of its limited solubility and solubilization capacity.

## Discussion

**Aggregate Structure and Catalytic Efficiency.** Three distinct types of the aqueous aggregate are obtainable from alkylammonium salts. An ammonium salt which contains a single, long-chain alkyl group (conventional surfactant) forms fluid, globular micelles. An alkylammonium salt with two long alkyl chains ( $C_{10}$ – $C_{20}$ ) produces huge aggregates with highly organized structure. An ammonium salt with three octyl chains forms fairly tight, small aggregates.<sup>27</sup> Some properties of these aggregates are summarized in Table I. A typical single-chain ammonium surfactant, CTAB, forms micelles at the concentration of  $8 \times 10^{-4}$  M. The bilayer-forming double-chain ammoniums possess cmc's of  $(1\text{--}3) \times 10^{-5}$  M.  $C_{18}C_8N^+2C_1$  which does not form bilayers possesses a higher cmc. The cmc of the triple-chain ammonium TMAC was estimated to be ca.  $3 \times 10^{-4}$  M. These cmc values correlate approximately with the total carbon number of the respective ammonium salt. Therefore, it is concluded that the cmc is predominantly determined by the hydrophobic–hydrophilic balance of a given ammonium salt without regard to the structural specificity.

(26) Kunitake, T.; Sakamoto, T. *Chem. Lett.* 1979, 1059–1062.

(27) Tridodecylmethylammonium bromide was recently prepared in these laboratories. This compound is soluble in water up to  $1 \times 10^{-4}$  M. The molecular weight of its aggregate was about  $10^5$  (the laser light scattering method), and no definite structure was found in electron microscopy.

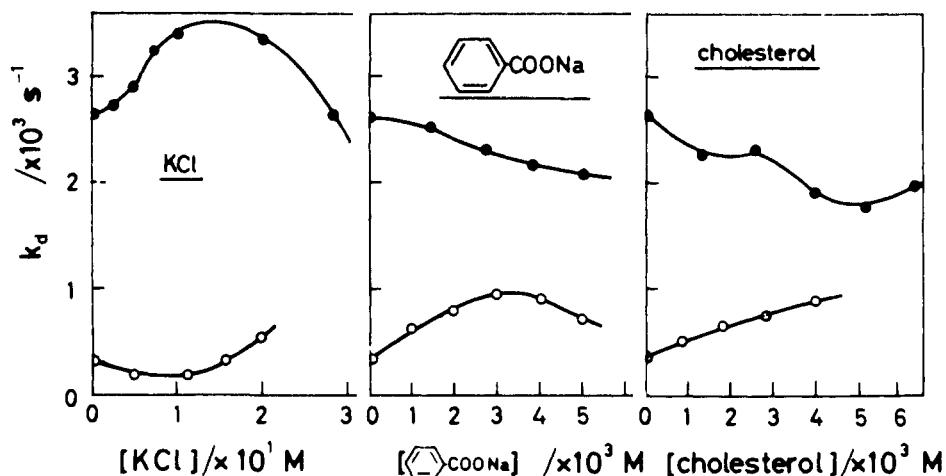


Figure 4. Effect of additives on the catalytic decarboxylation by the  $2C_{12}N^+2C_1$  bilayer (●) and the CTAB micelle (○): 30 °C, pH 9.1, 0.02 borate buffer,  $\mu = 0.01$  (KCl),  $[2C_{12}N^+2C_1] = [CTAB] = 1 \times 10^{-3}$  M, [substrate] =  $7.7 \times 10^{-5}$  M.

Table I. Physicochemical Properties of Ammonium Aggregates and Decarboxylation Rate

ammonium salt	total carbon no.	$10^4$ cmc, <sup>a</sup> M	$10^4$ (aggregate <sup>b</sup> wt), dalton	aggregate morphology	$10^3k_d$ at 30 °C, <sup>c</sup> s <sup>-1</sup>
single-chain					
CTAB ( $C_{16}N^+3C_1$ )	19	8	4	globular micelle	0.35
double-chain					
$2C_{18}N^+2C_1$	38	0.1	1000	bilayer	1.2
$2C_{16}$	34	0.08	800	bilayer	2.8
$2C_{14}$	30	0.1	500	bilayer	2.7
$2C_{12}$	26	0.3	100	bilayer	3.0
$C_{18}C_{16}N^+2C_1$	36		2000	bilayer	2.8
$C_{18}C_{14}$	34		2000	bilayer	2.8
$C_{18}C_{12}$	32	0.2	800	bilayer	2.3
$C_{18}C_{10}$	30		300	bilayer	2.8
$C_{18}C_8$	28	3	30	no ordered aggregate	0.8
triple-chain					
TMAC ( $3C_8N^+C_1$ )	25	ca. 3	<1	small, tight aggregate	7.2

<sup>a</sup> Obtained from the dye (2,6-dichlorophenolindophenol) method. [indophenol] =  $5 \times 10^{-6}$  M. <sup>b</sup> Determined by the light scattering method; Union Giken Co. Ltd., Model LS-600. He-Ne laser. <sup>c</sup> These values were estimated at [ammonium salt] =  $1 \times 10^{-3}$  M except for [TMAC] =  $2 \times 10^{-4}$  M.

In contrast, the mass of the ammonium aggregate varies drastically depending on their structural characteristics. The aggregate weight of CTAB is  $4 \times 10^4$  daltons, and that of TMAC was estimated to be less than  $1 \times 10^4$ . The aggregate weight of the dialkylammonium bilayer is extremely large: (0.1–2)  $\times 10^7$  daltons. Again,  $C_{18}C_8N^+2C_1$ , dialkylammonium which does not form bilayers, gives an aggregate weight of  $3 \times 10^5$  which is in between those of the CTAB micelle and the dialkylammonium bilayers. These results indicate that the mass of aqueous aggregates is highly dependent on the chemical structure of ammonium salts.

The rate constant of decarboxylation at 30 °C is summarized also in Table I. The reaction is accelerated in the presence of ammonium amphiphiles in the following order: triple-chain > double-chain > single-chain. These relative rates can be correlated neither with the total carbon number (as a measure of hydrophobicity) nor with the aggregate weight. It is therefore suggested that the very local microenvironment is the most influential factor for the rate enhancement.

It cannot be doubted that the decarboxylation of **1** is accelerated in the hydrophobic environment. For example, the extent of the rate enhancement could be correlated quantitatively with the hydrophobic nature of the microenvironment which was estimated by the  $\lambda_{max}$  shift of Methyl Orange in the case of alkylated polyvinylpyridines (polysoaps).<sup>18</sup> The remarkable acceleration of decarboxylation by the TMAC aggregate is in line with the equally remarkable rate enhancement observed for the nucleophilic acyl transfer<sup>7</sup> and the proton abstraction.<sup>9</sup> In the latter reactions as well, the TMAC aggregate activated hydrophobic, anionic reagents

much more efficiently than single-chain and double-chain ammonium salts did. It is suspected that, among the alkylammonium salts, the TMAC aggregate forms the most intimate ion pair with the carboxylate substrate because of the trialkyl structure.

**Membrane Fluidity and Catalytic Effect.** Peculiar catalytic effects of the ammonium bilayer membrane have been observed recently in these laboratories. In the hydrolysis of phenyl esters by a cholesteryl nucleophile, the intravesicle reaction was much faster than the intervesicle counterpart,<sup>28</sup> and the cholesteryl nucleophile was specifically activated when being compared with other hydrophobic nucleophiles.<sup>8</sup> The Arrhenius plots showed inflections near  $T_c$  in the acyl transfer<sup>26</sup> and in the proton abstraction.<sup>9</sup> On the other hand, simple, though efficient, rate acceleration was reported for thiolysis of *p*-nitrophenyl acetate<sup>29</sup> and for alkaline cleavage of the Ellman reagent.<sup>3</sup>

The peculiar catalytic effect of the ammonium bilayer is similarly observed in the decarboxylation reaction. Referring to the past literature, this reaction is expected to be facilitated increasingly with the increasing chain length (i.e., increasing hydrophobicity) of dialkylammonium bilayers. This is not necessarily the case. Figure 1 shows that  $2C_{18}N^+2C_1$  is less effective than  $2C_{12}N^+2C_1$  at 15 and 30 °C. The Arrhenius plots of Figure 2 clearly show that the microenvironment of the dialkylammonium bilayer change at temperatures close to the respective  $T_c$ 's. As

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Table II. Activation Energy of Decarboxylation

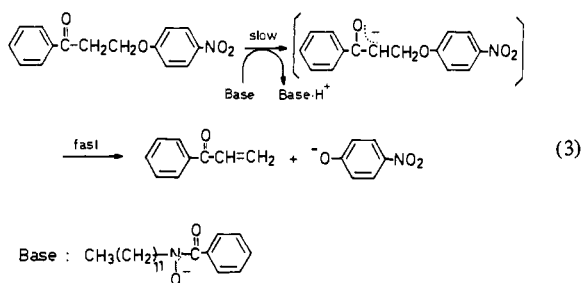
ammonium aggregate	$E_a$ , kcal/mol	
	below $T_c$	above $T_c$
CTAB		(20)
$2C_{12}N^+2C_1$	18	25
$2C_{14}N^+2C_1$	22	20
$2C_{16}N^+2C_1$	25	19
$2C_{18}N^+2C_1$	28	14
$2C_{16}N^+2C_1^a$	46	20

<sup>a</sup> The data for proton abstraction (ref 9).

expected, the CTAB system gives a single line.

Table II summarizes the activation energy  $E_a$  calculated from the slope of the Arrhenius plots. Rather curious trends are found for the  $E_a$  variation. In the temperature range below  $T_c$ ,  $E_a$  increases with increasing chain lengths of the dialkylammonium bilayer from 18 kcal/mol for  $2C_{12}N^+2C_1$  to 28 kcal/mol for  $2C_{18}N^+2C_1$ . At temperatures above  $T_c$ , the trend is reversed and  $E_a$  decrease with the increasing chain length from 25 kcal/mol ( $2C_{12}N^+2C_1$ ) to 14 kcal/mol ( $2C_{18}N^+2C_1$ ). The last figure may not be fully reliable, since the range of the reaction temperature above  $T_c$  is rather narrow for the  $2C_{18}N^+2C_1$  membrane. However, the trend of  $E_a$  decrease in this series is unmistakable. These contrasting trends above and below  $T_c$  may be interpreted in terms of hydrophobicity and fluidity of the bilayer membrane. When the bilayer is fluid at temperatures above  $T_c$ , the acceleration effect may be governed mainly by the hydrophobic effect. The decarboxylation is accelerated by the hydrophobic microenvironment. Since the membrane hydrophobicity increases with increasing chain lengths, the  $2C_{18}N^+2C_1$  membrane would give the lowest  $E_a$  value. At temperatures below  $T_c$ , the membrane fluidity becomes influential, and the most fluid  $2C_{12}N^+2C_1$  membrane should give the lowest  $E_a$  value. The suppressed rate-enhancing effect of rigid bilayer membranes is apparent from Figure 1. It is interesting that  $E_a$  of a moderately rigid membrane ( $2C_{12}N^+2C_1$  below  $T_c$ ) is smaller than that of a very fluid membrane ( $2C_{12}N^+2C_1$  above  $T_c$ ).

A very large  $E_a$  difference (46 and 20 kcal/mol) has been found for proton abstraction reaction<sup>9</sup> (eq 3). This reaction is bimo-



lecular, and its rate will be influenced not only by the membrane fluidity but also by the phase separation phenomenon in the membrane. Therefore, the  $E_a$  data cannot be discussed as straightforwardly as that of the unimolecular decarboxylation. In any case, this reaction possesses a very high  $E_a$  value in the rigid matrix (below  $T_c$ ) of the  $2C_{16}N^+2C_1$  membrane.

Discussion of the suppressed rate enhancement by the rigid membrane is in order. The rate enhancement of the decarboxylation reaction may be affected by both of the two elementary processes of Scheme I: the first is the binding of the carboxylate onto the ammonium aggregate and the second is the chemical transformation (decarboxylation) of the carboxylate-ammonium ion pair. Unfortunately, quantitative separation of these two processes cannot be made, as discussed above. However, a tentative application of eq 2 (see above) suggests that the substrate binding ( $K$ ) term is fairly invariable, and examination of Figure 1 indicates that the relative rate at  $1 \times 10^{-3}$  M ammonium concentrations may be discussed in terms of  $k_d''$  (rate constant at saturation).

Two factors are conceivable as the cause of the relative inefficiency of the rate enhancement at temperatures below  $T_c$ . In the first, the molecular packing and orientation of the ammonium bilayer changes at  $T_c$ .<sup>4</sup> This change may cause alteration of the microenvironment (e.g., electrostatic potential) of the membrane surface where the reaction may take place and lead to the difference in  $k_d''$  processes. As the second possibility, if the catalytic site is in the hydrophobic membrane matrix, the reaction will be facilitated more readily with fluid ammonium bilayers. At temperatures below  $T_c$  the rigid membrane will not allow formation of tight ammonium-substrate ion pair and the rate-enhancing effect will be relatively small. We cannot decide which factor is more important.

### Conclusion

The decarboxylation reaction of **1** has been used extensively as a kinetic probe of the medium effect. The present study further shows that this reaction is quite useful for clarifying the fundamental difference in the catalytic effect of three, representative ammonium aggregates. It is interesting that single-chain, double-chain, and triple-chain ammonium salts produce very distinctive aqueous aggregates with different microenvironments. An exciting possibility arises that the morphology and the microenvironment of aqueous alkylammonium aggregates can be varied over a wide range by using properly selected combinations of the alkyl group.

Alkylammonium salts with two, long alkyl chains form stable bilayer membranes. The membrane fluidity can be varied rather extensively because of the ordered nature of the membrane. Thus, apart from its implication as a biomembrane model, the bilayer membrane provides reaction sites whose microenvironments can be varied over a range much wider than those of the conventional fluid micelle.