The Solvolysis of Benzoyl Chloride in Water-Acetone Mixtures **Under High Pressure**

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By using a complete rate constant(k_e) which treats a solvent (water) as a reactant, and a conventional rate constant(k_e), which ignores the solvent in describing the rate, the parameters ΔV_i^* , ΔH_i^* and ΔS_i^* were introduced. These quantities represent the volume change, the enthalpy change, and the entropy change accompanying the electrostriction which occurs when solvent molecules condense on the activated complex. The authors measured the rates of the solvolysis of benzoyl chloride in wateracetone mixtures at 15° to 30°C and 1 bar to 2500 bars. Applying the authors' theory to the experimental results, the parameters, ΔV_{*}^{*} , ΔH_{*}^{*} and ΔS_{*}^{*} were evaluated, and it was found that they are all negative, indicating that water dipoles condense on the activated complex. They also proposed the following equations: $\Delta H_c^* = \Delta H_c^* + \Delta H_c^*$ and $\Delta S_c^* = \Delta S_c^* + \Delta S_c^*$, where ΔH_c^* and ΔS_i^* are the activation enthalpy change and the activation entropy change for the conventional reaction rate, respectively, and ΔH_{τ}^{*} and ΔS_{τ}^{*} are the corresponding quantities for the complete reaction rate. The authors proposed that for the SN_1 type, all the quantities, ΔH_1^a , ΔS_1^a , ΔH_2^a and ΔS_2^a are comparatively large, and for the SN_1 type, these quantities are smaller than for the SN_1 type, and occasionally the case $\Delta S_c^* < 0$ occurs. Using these criteria, the authors concluded that at high temperature, high pressure and for a high water content solvent, the SN₁ type mechanism predominates whereas in the reversed case the SN_2 type predominates.

Introduction

Owing to the the advancement of high pressure chemistry during the last two decades, the electrochemistry for aqueous inorganic salt solutions has highly developed, this is partly due to the fact that the complete equilibrium constant (K°) , which includes solvent(H2O) as a reactant, was exactly defined.1-3 The conventional equilibrium constant (K), which does not include the solvent as a reactant, cannot describe the electrostriction effect between dissociated ions and solvent molecules, whereas K^o especially has the merit to treat this effect4-8.

Marshall et al have obtained various thermodynamic parameters derived from Ko in their papers2.3.6-8. They found experimentally that the conventional molar volume change (ΔV) is proportional to the compressibility of the solvent, and have obtained a hydration number change (k, n) in our paper) and complete thermodynamic parameters (ΔH_o , ΔS_o). They also introduced the complete rate constant⁸ (r_o, k_e in our paper). But they failed to define electrostriction parameters which have very important meaning in kinetics.

Therefore, in the present paper, the electrostriction parameters $(\Delta V_s^*, \Delta H_s^*)$ and ΔS_s^* are defined from the relation between the conventional rate constant(k_c) and the complete rate constant(k,), which could be called the exact rate constant, thus the subscript, e is used in this paper. Using these definition for electrostriction parameters a theory of reaction kinetics for solvolysis was developed, and it was applied to the solvolysis of benzoyl chloride in water-acetone mixture

In this paper, we report our experimental results obtained by measuring the rates of the solvolysis under high pressure. From the rate constants k_c and k_c obtained by experiment, the

parameters ΔV_{s}^{*} , ΔH_{s}^{*} , and ΔS_{s}^{*} were evaluated by analysis. It was found that the new parameters ΔV_{*}^{*} , ΔH_{*}^{*} and ΔS_{*}^{*} have all negative values indicating that water dipoles condense into the activated complex.

The variation of conventional thermodynamic parameters $(\Delta V_{\bullet}^{*}, \Delta H_{\bullet}^{*})$ and ΔS_{\bullet}^{*}) with pressure, temperature and water content could be interpreted more concretely by using the change of ΔV_s^* , ΔH_s^* and ΔS_s^* with these variables. From the evaluation of all parameters entering in our theory, we were able to predict the degree of the critical bond elongation and the charge separation in the activated complex.

Many papers were reported for the solvolysis of benzoyl chloride, but the mechanism have not been clearly determined⁹⁻¹¹. In this paper, we shall consider the mechanism from our viewpoint, and decide to which of the SN_1 and SN_2 types the reaction of benzoyl chloride belongs from our criteria which were newly formulated.

Theory

The mechanism of the solvolysis of benzoyl chloride is considered to be as follows:

$$\phi \text{COCl}(aq)_{n} + n\text{H}_{2}\text{O} \rightarrow \{\phi \text{CO}^{+}(aq)_{n^{+}} \cdots \text{Cl}^{-}(aq)_{n^{-}}\}^{+}
\rightarrow \phi \text{COO}^{-}(aq)_{n^{-}} + 2\text{H}^{+}(aq)_{n^{+}} + \text{Cl}^{-}(aq)_{n^{-}}$$
(1)

where the following relations hold:

$$j + n = n^+ + n^- \tag{2a}$$

$$n^+ + n^- < m^- + 2m^+ + 1^-$$
 (2b)

The rate of Eq.(1) is expressed by

$$Rate = k_e (H_2O)^n (\phi COCl(aq),)$$
 (3)

where

$$\mathbf{k}_{c} = \mathbf{k}_{e} (\mathbf{H}, \mathbf{O})^{n} \tag{5}$$

In the above, k_c is so-called the conventional rate constant, and k_c is called "the complete rate constant", after Marshall's nomenclature. One notes that in Eq.(4) the solvent H₂O is ignored in the rate expression according to the conventional method. From Eq.(5), one obtains

$$\ln k_c = \ln k_e + n \ln (H_2 O) \tag{6}$$

Thus the plot of $\ln k_c vs. \ln[H_2O]$ at various pressures yields a straight line, the slope of which is n, while the intercept gives $\ln k_c$. In our experiment, k_c and $[H_2O]$ in Eq.(6) are functions of pressure, thus n and k_c are not a function of pressure over the range studied in the present study.

From Eq.(6) one obtains the following equations:

$$\left(\frac{\partial \ln k_c}{\partial P}\right)_T - \left(\frac{\ln k_e}{\partial P}\right)_T = n\left(\frac{\partial \ln(H_2O)}{\partial P}\right) = n\beta \tag{7a}$$

and

$$(\partial \ln k_c/\partial P)_{\tau} = n\beta \tag{7b}$$

where

$$\beta = \left(\frac{\partial \ln H_2 O}{\partial P}\right)_{\tau} \tag{8}$$

and it is the compressibility of water. By multiplying both sides of Eq.(7a) by - RT, the following equation results:

$$\Delta V_c^* + \Delta V_e^* = -nRT\beta \tag{9a}$$

where

$$\Delta V_i^* = -RT \left(\frac{\partial \ln k_i}{\partial P} \right)_T \quad (i = c \text{ or } e, k_i = \text{rate const.})$$
 (9b)

In the above, ΔV_c^* is the conventional activation volume change, and ΔV_c^* is the complete activation volume change. We define $\Delta V_s^* = \Delta V_c^* - \Delta V_c^*$ which is called here the electrostriction volume change in the activated complex. Since in our experiment $\Delta V_s^* \cong 0$ because of the independency of k_c on P, one obtains from Eq.(9):

$$\Delta V_c^* \simeq \Delta V_c^* = -nRT\beta \tag{10}$$

The following equation is also derived from Eq.(6):

$$\left(\frac{\partial \ln k_c}{\partial T}\right)_{P} - \left(\frac{\partial \ln k_c}{\partial T}\right)_{P} = n \left(\frac{\partial \ln (H_2 O)}{\partial T}\right)_{P} + \left(\frac{\partial n}{\partial T}\right)_{P} \ln (H_2 O)$$

$$= -n_a + \left(\frac{\partial n}{\partial T}\right)_{P} \ln (H_2 O) \tag{11}$$

where

$$\alpha = -\left(\frac{\partial \ln\left(\mathbf{H_2O}\right)}{\partial T}\right)_P \tag{12}$$

and it is the thermal expansion coefficient of water. By multiplying both sides of Eq.(11) by RT², we obtain the following equation:

$$\Delta H_c^* - \Delta H_e^* = RT^2 \left(-n\alpha + \left(\frac{\partial n}{\partial T} \right)_P \ln(H_2O) \right)$$
 (13)

where ΔH_{ϵ}^{*} and ΔH_{ϵ}^{*} are the conventional activation enthalpy

change, and the complete activation enthalpy change, respectively.

We define $\Delta H_s^* = \Delta H_c^* - \Delta H_c^*$ which is called here the electrostriction enthalpy change in the activated complex. Thus Eq.(13) is expressed as

$$\Delta H_s^* = RT^2 \left(-n\alpha + \left(\frac{\partial n}{\partial T} \right)_P \ln[H_2O] \right) \tag{14}$$

The reason why ΔH_i^* is called as such is considered in the following. As the definition $\Delta H_i^* \equiv \Delta H_i^* - \Delta H_i^*$ shows, this quantity related to the difference of ΔH_i^* from k_c for Eq.(4) and ΔH_i^* from k_c for Eq.(3), *i.e.*, it is due to n molecules of water participated in the formation of activated complex [see Eq.(1)], where the water dipoles are attracted to the activated complex in which a partial charge separation occurred. This fact is also substanciated by Eq.(14), since its right hand side includes only the quantities related to the n molecules of water. One may also note that during the condensation of n molecules of water, the redistribution of n water molecules occurrs in the activated complex as one sees from eq.(2a). The quantity of $\Delta V_i^* \equiv \Delta V_i^* - \Delta V_i^*$ which was mentioned previously is similarly understood as in the case of ΔH_i^* .

We consider next, the activation entropy change. Since

$$\Delta G_{i}^{+} = -RT \ln \frac{h k_{i}}{kT} (i = c \text{ or } e, k_{i} = \text{rate const.})$$

and since $\Delta S_i^* = -[\partial (\Delta G_i^*)/\partial T]_P$, we obtain

$$\Delta S_{t}^{\star} = RT \left(\frac{\partial \ln k_{t}}{\partial T} \right)_{P} + R \left(\ln \frac{h k_{t}}{kT} - 1 \right)$$
 (15a)

and

$$\Delta S_c^* - \Delta S_e^* = RT\left(\left(\frac{\partial \ln k_c}{\partial T}\right)_P - \left(\frac{\partial \ln k_c}{\partial T}\right)_P\right) + R\ln\left(\frac{k_c}{k_c}\right)$$
(15b)

In Eq.(15b), ΔS_c^* and ΔS_c^* are the conventional activation entropy change and the complete activation entropy change, respectively.

Let us define $\Delta S_s^* = \Delta S_c^* - \Delta S_c^*$. By substituting Eqs. (6) and (11) to (15b), one obtain

$$\Delta S_s^* = RT \left[-n\alpha + \left(\frac{\partial n}{\partial T} \right)_F \ln[H_2O] \right] + nR \ln[H_2O]$$
 (16)

The quantity ΔS_i^* is called here the electrostriction entropy change in the activated complex, *i.e.*, it is the entropy change due to the condensation of n water molecules.

Experimental

- **A. Materials.** Acetone was purified by drying over calcium chloride followed by fractional distillation, and benzoly chloride was purified by vacuum distillation.
- B. Conductance Bridge and Conductance Cell. The conductance bridge is composed of B.N. 532 capacitor, B.N. 332 resistor and B.N. 12 12/2 detector made by Rohde Schwarz Co., Germany. The conductance cell (Figure 1) is composed of two parts, a glass tube stopper of about 4 cm and a glass tube holder of electrolyte solution of 8 cm long, both being 1 cm in diameter Two Pt circular plate electrodes are sealed to the holder as shown in Figure 1. The upper stopper of the cell was filled with a few grams of mercury to keep the sample from escaping out of the holder in the case when the latter is pushed upward while the cell is set in the pressure reservoir vessel.

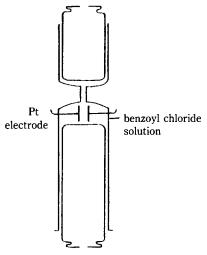


Figure 1. Schematic drawing of the electroconductance cell.

The cell was made by using two glass hypodermic syringes and by modifying them. The pressure measurement system was described elsewhere.¹²

C. Density Measurement of Water-Acetone Mixture Solvents. The piezometer originally due to Aime 13 is used as the density measurement cell. The sample bottle is made of hard glass, about 10 cm^3 . The upper stopper of the cell prevents the oil, which is used as the transmittance medium of pressure, from infiltrating into the bottle. A small mercury reservoir is attached to the bottle. An inlet projector is attached to the bottle of the bottle through the projector. Before measuring the density of solvent mixtures, the exact volume of the sample bottle, V_{bontle} , was determined under pressure and at several temperatures with necessary corrections. The density of water-acetone mixture at a given pressure and temperature is determined by the following procedure: (1) the sample bottle is filled with the water-acetone

mixture, the mercury volume V_{Hg} entered into the bottle, when the latter is under pressure, was evaluated with corrections of the compressibility and expansion coefficient¹⁴ of mercury, (2) the solvent-mixture weight W_{mix} was measured at a given temperature, and then (3) the density of the mixture ρ_{mix} is calculated by $\rho_{mix} = W_{mix}/(V_{bonle} - V_{Hg})$.

The mole concentration of water[H₂O] in the mixture solvent, which is important in the later calculation, is obtained from the following equation:

$$(H_2O) = \frac{1000 \rho_{mix}}{18.016} \chi_{H_2O}$$
 (17)

where, χ_{H_2O} is the mole fraction of water in the water–acetone mixture.

D. Kinetic Measurement. The conductance cell (Figure 1) is also used as a reaction vessel. The conductance cell is suspended in a high pressure vessel¹² with electrode leads, the vessel being set in a thermostat.

The rates of the solvolysis are determined by measuring the conductance of the solution since the conductance increases with time because of the production of ØCOO-, H* and Cl- ions as shown in Eq.(1). All kinetic runs were carried out under pseudo first order conditions¹⁵. The Guggenheim plots¹⁶ were used in this experiment since the conductance at infinite time was not determined. All the conductance measurements in this experiment were conducted from 1 to 2500 bars and from 15° to 30°C.

Result

- A. Densities of Water-Acetone Mixtures. Table 1 shows the density data of water-acetone mixtures measured at various pressures and temperatures. In Table 1, they are also included the mole concentrations of water, [H₂O], in the mixtures which were calculated by using Eq.(17).
- **B.** Conventional and Complete Rate Constants. The conventional rate constant k_{ϵ} Eq.(4) observed for the solvolysis

Table 1. Densities (g/cm³) and mole Concentrations (mole/l) of Water in Water-acetone Mixtures"

	P (bars)	1	500	1000	1500	2000	2500
	wt%(H₂O)		,				
15°C	5	0.8147	0.8667	0.9085	0.9428	0.9721	1.0012
		(6.5594)	(6.7981)	(7.3147)	(7.5908)	(7.8267)	(8.0610)
	10	0.8329	0.8816	0.9223	0.9552	0.9846	1.0135
		(12.1921)	(12.9049)	(13.5007)	(13.9823)	(14.4127)	(14.8357)
20°C	5	0.8097	0.8621	0.9048	0.9397	0.9693	0.9985
		(6.5192)	(6.9411)	(7.2849)	(7.5654)	(7.8042)	(8.3093)
	10	0.8285	0.8781	0.9192	0.9523	0.9824	1.0117
		(12.1276)	(12.8536)	(13.4553)	(13.9398)	(14.3801)	(14.8093)
25°C	5	0.8048	0.8575	0.9011	0.9366	0.9666	0.9959
		(6.4797)	(6.9040)	(7.2551)	(7.5409)	(7.7824)	(8.1083)
	10	0.8241	0.8747	0.9161	0.9496	0.9803	1.0100
		(12.0632)	(12.8039)	(13.4099)	(13.9003)	(14.3497)	(14.7845)
30°C	5	0.7999	0.8530	0.8975	0.9336	0.9639	0.9923
		(6.4403)	(6.8678)	(7.2261)	(7.5167)	(7.7607)	(7.9974)
	10	0.8198	0.8713	0.9131	0.9471	0.9782	1.0084
		(12.0003)	(12.7542)	(13.3660)	(13.8623)	(14.3190)	(14.7610)

[&]quot;In this table, the parenthesized data are the mole concentrations of water whereas the unparenthesized data indicate the densities of water-acetone mixture solvent.

Table 2. Conventional rate Constants (k.), Complete rate Constants (k.) and Hydration Number Change (n) of the Solvolysis of Benzoyl Chloride in Water-acetone Mixtures

		k.×1010a sec-1(l/mole)a	$k_c \times 10^4 \text{ (sec}^{-1})$					
			1	500	1000		2000	
			(bar)	(bars)	(bars)	(bars)	(bars)	(bars)
	wt%(H₂O)							
15°C	5	5.78	0.84	1.28	1.76	2.19	2.65	3.07
		(6.33)						
	10	0.07	1.82	2.51	3.39	4.59	5.47	6.76
		(6.79)						
20°C	5	17.35	1.16	1.71	2.21	2.75	3.32	3.84
		(5.92)						
	10	0.32	2.39	3.47	4.59	5.92	7.41	8.48
		(6.35)						
$25^{\circ}\mathrm{C}$	5	41.64	1.42	2.08	2.67	3.30	4.00	4.75
		(5.59)						
	10	0.98	3.18	4.56	6.05	7.38	9.75	10.35
		(6.02)						
30°C	5	78.80	1.74	2.45	3.21	4.01	4.77	5.53
		(5.37)						10.0
	10	3.11	4.34	6.37	8.41	10.16	11.91	13.68
		(5.70)						

[&]quot;The parenthesized data are the hydration number changes (n).

of benzoyl chloride in water-acetone mixtures are shown in Table 2. The larger the weight percentage of water, the larger are the rate constants. The value of k_c increases with temperature and pressure.

The values of $\ln k_c$ from Table 2 are plotted against $\ln[H_2O]$ from Table 1 in Figure 2. The slopes of the straight lines give the values of n and are tabulated in Table 2. The intercepts give the values of the complete rate constant k_c which are tabulated in Table 2. The quantities of k_c and n may change with pressures, but in the range of pressures studied in our experiment, they are about constant, and independent of pressures (see Figure 2). Marshall⁸ reported that the n value is independent of temperatures and pressures, this fact, however, is contradictory to our results, i.e., in our case n is independent of pressures, but it decreases with increasing temperatures. Concerning to k_c , Marshall also noticed that it is independent of pressures in agreement with our result.

C. Compressibility and Thermal Expansion Coefficient. The compressibility β of water at a given concentration and temperature is calculated from Eq.(8) by utilizing the [H₂O] data in Table 1. [Note: The ln [H₂O] data were expressed in a power series, and β was obtained by differentiation in accordance with Eq.(8). Other differential quantities in this paper were also obtained by similar method.] The results are summarized in Table 3. The thermal expansion coefficient α is similarly calculated from Eq.(12) by using the [H₂O] data of Table 1, and are also tabulated in Table 3. In Table 3, the square bracketed data of β were obtained from Eq.(7b), i.e., from the rate data k_c . The agreement between the β values from the [H₂O] and from the k_c values is very good. This shows that Eq.(5) is right.

D. Conventional Activation Volume Change. The con-

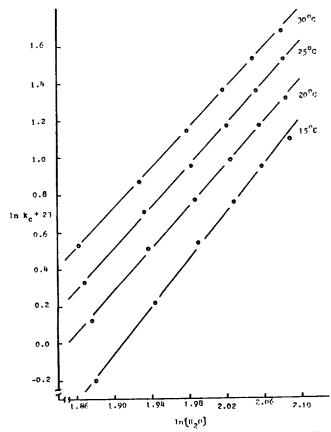


Figure 2. The plot of $\ln k_c$ vs. $\ln[H_2O]$ at 5 wt% of water. The temperature is indicated on each curve.

ventional activation volume change ΔV_e^* is calculated from Eq.(10) by using the n value in Table 4. From Table 4, we note that (1) all ΔV_e^* values are negative, (2) the value of $|\Delta V_e^*|$ decreases with increasing pressure and temperature, and (3) the value of $|\Delta V_e^*|$ increases with increasing wt% of water.

All the above experimental facts are consequence of Eq.(10). But it will be interesting to consider significant physical reasons embodied in each item. The ΔV_{ϵ}^* is equal to $\Delta V_c^* - V_o$, where ΔV_c^* is the volume of the activated complex shown in the reaction mechanism Eq.(1), and V_o is the volume of reactants i.e., $V_o = V[\varnothing COCl(aq)_i] + V(n H_2O)$. The fact described in item (1) is natural since V_o should be larger than the volume of the hydrated activated complex. Next, we explain the fact of item (2). The value of V[ØCOCl(aq),] does not change greatly with pressure and temperature, while V(n H₂O) decreases with pressure since n H₂O is the free water acting as a reactant, and it decreases with increasing temperature because of the decrease of n with temperature (see Figure 2 and Table 2). Thus, V. decreases with pressure and temperature. The V_{ϵ}^* value does not change with pressure and temperature, since the hydrated water strongly attached to the activated complex by dipole-dipole interactions. Consequently, $|\Delta V_c^*|$ (= $|V_c^* - V_o|$) decreases with increasing pressure and temperature since $V_{\bullet}^* < V_{\bullet}$ and, the latter decreases with P and T as mentioned above. The fact of item (3) is explained below. According to Table 2, the n value for 10 wt% water is larger than that for 5 wt%. Thus, | ΔV_c^* | becomes larger for 10 wt% water than for 5 wt% at a given temperature and pressure as expected from Eq.(10).

E. Activation Enthalpy and Activation Entropy. The

Table 3. Compressibilities (β×10⁴ bar⁻¹) and Thermal Expansion Coefficient (α × 10³ deg.⁻¹) of Water-acetone Mixtures^{-1,6}

	P (bars)	1	500	1000	1500	2000	2500
	wt%(H ₂ O)						
15°C	5	1.4970	1.0434	0.9052	0.7439	0.5584	0.3747
		(1.2112)	(1.0539)	(0.8073)	(0.6506)	(0.5624)	(0.5621)
		[1.3211] ^c	[1.1213]	[0.9089]	[0.6959]	$[0.4828]^{c}$	[0.2784]
	10	1.0870	0.9851	0.8574	0.7087	0.5457	0.3714
		(1.0486)	(0.7789)	(0.6651)	(0.5723)	(0.4334)	(0.3355)
20°C	5	1.1914	1.0752	0.9256	0.7507	0.5570	0.3798
		(1.2186)	(1.0595)	(0.8106)	(0.6528)	(0.5640)	(0.5275)
	10	1.1052	1.0072	0.8731	0.7216	0.5557	0.3780
		(1.0541)	(0.7820)	(0.6673)	(0.5741)	(0.4343)	(0.3361)
25°C	5	1.2135	1.0952	0.9430	0.7642	0.5657	0.3830
		(1.2261)	(1.0652)	(0.8139)	(0.6549)	(0.5656)	(0.5289)
	10	1.1358	1.0286	0.8919	0.7324	0.5577	0.3703
		(1.0592)	(0.7851)	(0.6696)	(0.5757)	(0.4353)	(0.3366)
30°C	5	1.2340	1.1123	0.9562	0.7718	0.5668	0.3868
		(1.2336)	(1.0781)	(0.8172)	(0.6570)	(0.5672)	(0.5303)
	10	1.1440	1.0395	0.9046	0.7465	0.5601	0.3867
		(1.0653)	(0.7881)	(0.6718)	(0.5772)	(0.4362)	(0.3372)

[&]quot;The parenthesized data are the thermal expansion coefficients of water-acetone mixtures, and the unparenthesized data are the compressibilities. "The β and α values of pure water at 15°C and one bar are; $\beta = 0.4678 \times 10$ bar-1 and $\alpha = 0.1507 \times 10^{-3}$ deg.-1 (Handbook of Chemistry and Physics, 55th ed. CRC Press, Clevland, Ohio, 1975, P. F-5). These velues are smaller than our mixture values as expected. These compressibility data were calculated from Eq.(7b) i.e., from k_c . Similar calculations of β were conducted in other cases than at 15°C and 5 wt% water content. But the results are not shown in this table.

Table 4. Conventional Activation Volume Change (△ V^{*}₂cm³/mole) for the Solvolysis of Benzoyl Chloride in Water-aceton Mixtures

	P (bars)	1	500	1000	1500	2000	2500
	wt%(H₂O)						
15°C	5	-17.43	- 15.82	-13.72	-11.28	-8.47	-5.68
	10	-18.15	-16.45	-14.31	-11.83	-9.11	-6.20
20°C	5	-17.19	-15.51	- 13.35	-10.83	-8.03	-5.48
	10	-17.70	-15.96	- 13.51	-11.17	-8.60	-5.85
25°C	5	-16.81	-15.17	-13.06	-10.59	-7.84	-5.31
	10	-16.95	-15.35	-13.31	-10.93	-8.32	-5.52
30°C	5	-16.70	-15.05	-12.94	-10.44	-7.67	-5.23
	10	-16.83	-15.13	-12.99	-10.72	-8.04	-5.55

conventional activation enthalpy change ΔH_c^* is obtained by a usual method, i.e., $\Delta H_c^* = RT^2$ ($\partial \ln k_c/\partial T$), where k_c was experimentally obtained. The complete activation enthalpy change ΔH_c^* is similarly obtained by using , which was also experimentally obtained [cf. Eq.(3)]. All the data of ΔH_c^* , ΔH_c^* , and ΔH_c^* obtained from our experiment are summarized in Table 5.

The conventional and complete activation entropies are calculated by using Eq.(15a) from the k, and k, values in Table 2. The ΔS_*^* ($\equiv \Delta S_*^*$ – ΔS_*^*) is calculated from Eq.(15b). All the values of ΔS_*^* , ΔS_*^* and ΔS_*^* are summarized in Table 6.

Discussion

A. Model of the Activated Complex. At the outset, the physical meaning of the numbers, n* and n*, should be clarified. As shown by Eq.(1), n* is the hydration number at the positive side of the activated complex whereas n* is that at the negative

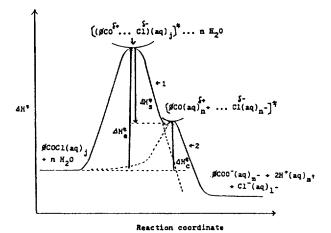


Figure 3. Diagram of ΔH^s vs. reaction coordinate. ΔH^s_c is the barrier height of the complete reaction (curve 1), ΔH^s_c is the electrostriction enthalpy in the activated complex, ΔH^s_c is the barrier height of the conventional reaction (curve 2). The upward direction of an arrow indicates a positive value whereas the downward arrow shows a negative value.

side. The sum, $(n^* + n^-)$ is equal to j + n [see Eq.(2a)]. Next, we consider the activated complexes corresponding to k_c and k_c . Since the two values are connected by Eq.(5), we obtain

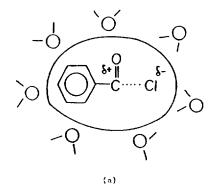
$$\Delta G_c^* = \Delta G_e^* - nRT \ln(H_2O) \tag{18}$$

We have already obtained Eq.(13) which expresses the relation between ΔH_c^* and ΔH_c^* . Equations (13) and (18) suggest that the curve of ΔH_c^* vs. reaction coordinate is represented by Figure 3, *i.e.*, curve 1 is for a complete reaction mech-

Table 5. Conventional Activation Enthalpy Change (ΔH_c^*) , the Complete Activation Enthalpy Change (ΔH_c^*) and the Electrostriction Enthalpy Change in the Activated Complex $(\Delta H_c^*) = \Delta H_c^* - \Delta H_c^*$ of the Solvolysis or Benzoyl Chloride in Water-acetone Mixtures

		∆H.(kcal/mole)		ΔH _c (kcal/mole) ^o							
			1 (bar)	500 (bars)	1000 (bars)	1500 (bars)	2000 (bars)	2500 (bars)			
	wt%(H ₂ O)										
15°C	5	28.26	8.46	7.38	6.24	5.89	5.49	5.48			
			(-19.80)	(-20.88)	(-22.02)	(-22.37)	(-22.77)	(-22.78)			
	10	38.06	9.21	9.77	9.57	9.12	8.66	7.97			
			(-28.85)	(-28.29)	(-28.49)	(-28.94)	(-29.40)	(-33.09)			
20°C	5	29.25	8.76	7.63	6.46	6.10	5.69	5.67			
			(-20.49)	(-21.62)	(-22.79)	(-23.15)	(-23.56)	(-23.58)			
	10	39.39	9.53	10.11	9.90	9.44	8.96	8.25			
			(-29.86)	(-29.28)	(-29.49)	(-29.95)	(-30.43)	(-31.14)			
25°C	5	30.26	9.06	7.90	6.68	6.31	5.88	5.86			
			(-21.20)	(-22.36)	(-23.58)	(-23.95)	(-24.38)	(-24.40)			
	10	40.75	9.86	10.46	10.25	9.77	9.27	8.53			
			(-30.89)	(-30.29)	(-30.50)	(-30.98)	(-31.48)	(-32.22)			
30°C	5	31.28	9.37	8.16	6.90	6.52	6.08	6.06			
-	_		(-21.91)	(-23.12)	(-24.38)	(-24.76)	(-25.20)	(-25.22)			
	10	42.13	10.19	10.81	10.59	10.10	9.56	8.82			
	10	-3120	(-31.94)	(-31.32)	(-31.54)	(-32.03)	(-32.54)	(-33.31)			

^{*}The parenthesized data are ΔH_{*}^{*} values.



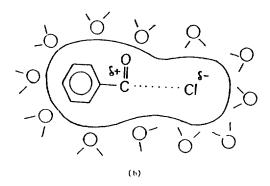


Figure 4. Models of activated complexes. Part (a) indicates an activated complex at 5% water content while (b) shows that at 10% water content. Note that the C-Cl bond elongated more at 10% water content than at 5% content, as a result, more charge separation occurred in the former (b) than in the latter case (a). Also one may note that more water dipoles are considered at 10% water content than at 5% content.

anisms, and curve 2 is a conventional reaction. It is assumed in Figure 3 that the critical bond (C-Cl) elongation in the activated complexes is about equal in the complete reaction and in the conventional reaction, the latter is hydrated $[\varnothing CO^{\bullet*}(aq)_n + ... Cl^{\bullet*}(aq)_n -]^*$ whereas the former is unhydrated i.e., $[(\varnothing CO^{\bullet}... Cl^{\bullet})(aq)]^*$... in H_2O , where is unhydrated as attached loosely to the activated complex, but not hydrated as in the conventional activated complex. It is also assumed that the complete reaction is a two-step reaction, the first is a bondelongation step, and the second is an electrostriction (hydration) step, the latter being very fast while the former is a rate determining step for the complete reaction. Thus $\Delta H_*^* (\equiv \Delta H_*^* - \Delta H_*^*)$, $\Delta S_*^* (\equiv \Delta S_*^* - \Delta S_*^*)$ and $\Delta V_*^* (\equiv \Delta V_*^* - \Delta V_*^*)$ are considered to be the quantities due to the electrostriction as previously mentioned.

Figure 4 shows schematically the activated complexes in 5 wt% and 10 wt% water. It is clear that in 10% solution, a greater charge separation and a more bond elongation occur, consequently, more condensation of water dipoles results than for 5 % solution.

B. Variation of ΔH_{\star}^{*} and ΔS_{\star}^{*} with Temperature and Water Content. According to Table 5, ΔH_{\star}^{*} with is independent of pressure, and increases with temperature and water content. As mentioned previously ΔH_{\star}^{*} is required for forming the activated complex $[(\emptyset CO^{\star} \dots Cl^{-})(aq)_{j}]^{\star} \dots n H_{\star}O$ in which the critical bond C-Cl is elongated, it seems that the bond elongation and the charge separation increases with increasing temperature and water content. Thus the above mentioned facts result.

The complete activation entropy change ΔS_{τ}^{*} is a positive quantity (Table 6) except ΔS_{τ}^{*} at 15°C and 5% water content, and it behaves in a similar way as ΔH_{τ}^{*} , i.e., it increases with temperature and water content. The reason for these facts is similar to that for ΔH_{τ}^{*} , i.e., the bond elongation and charge

Table 6. Conventional Activation Entropy Change (45), the Complete Activation Entropy Change (45) and the electrostriction Entropy Change in the Activated Complex ($\Delta S_t^* = \Delta S_t^* - \Delta S_t^*$) of the Solvolysis of Bnezoyl Chloride in Water-acetone Mixtures

		∆ S _e (e.u.)			$\Delta S_c(\mathrm{e.u.})^c$				
			1 (bar)	500 (bars)	1000 (bars)	1500 (bars)	2000 (bars)	2500 (bars)	
	wt%(H ₂ O)								
15°C	5	-2.67	-47.74	-50.68	-53.91	- 54.77	- 55.76	- 55.53	
			(-45.07)	(-48.01)	(-51.24)	(-52.10)	(-53.09)	(-52.86)	
	10	22.59	-43.63	-41.04	-41.13	-42.08	-43.33	- 45.31	
			(-66.22)	(-63.63)	(-63.72)	(-64.67)	(-65.92)	(-67.90)	
20°C	5	1.19	-46.62	- 49.69	-53.20	-54.00	-55.02	-54.79	
			(-47.81)	(-50.88)	(-54.39)	(-55.19)	(-56.21)	(-55.98)	
	10	27.87	-42.57	-39.84	-39.99	-41.05	-42.24	-44.42	
			(-70.44)	(-67.71)	(-67.86)	(-68.92)	(-70.11)	(-72.29)	
25°C	5	4.63	-45.75	-48.90	-52.49	-53.31	-54.35	-54.07	
			(-50.38)	(-53.53)	(-57.12)	(-57.94)	(-58.98)	(-58.70)	
	10	32.37	-41.48	-38.75	-38.89	-40.10	-42.21	-43.58	
			(-73.85)	(-71.12)	(-71.26)	(-72.47)	(-74.58)	(-75.95)	
30°C	5	7.85	-44.86	-48.16	-51.78	-52.60	-53.70	-53.47	
			(-52.41)	(-55.71)	(-59.33)	(-60.15)	(-61.25)	(-61.02)	
	10	36.91	-40.34	-37.53	-37.70	-38.95	-40.32	-42.57	
			(-77.25)	(-74.44)	(-74.61)	(-75.86)	(-77.23)	(-79.48)	

[&]quot;The parenthesized data are ΔS_s^* values.

separation in the formation of the activated complex increase with temperature and water content.

C. Variation of ΔH_s^* and ΔS_s^* with Pressure, Temperature and Water Content. According to Table 5 and 6, ΔH_s^* and ΔS_s^* are all negative, this is natural because ΔH_s^* and ΔS_s^* are the enthalpy and entropy changes due to the condensation of water dipoles on the activated complex. Also we note that $|\Delta H_s^*|$ and $|\Delta S_s^*|$ increases with increasing pressure, for 5% water content. This is explained by Eqs. (14) and (16), where ($\partial n/\partial T$), is a negative quantity, and [H₂O] increases with increasing pressure, thus $|\Delta H_s^*|$ and $|\Delta S_s^*|$ increase with P. In Tables 5 and 6, $|\Delta H_s^*|$ and $|\Delta S_s^*|$ for 10 wt% content show a minimum at 500 bars; then they increase regularly. At present, the reason for this phenomenon is not clear. We note, however, that $|\Delta H_s^*|$ and $|\Delta S_s^*|$ generally increase with P, this fact is physically understood in the following way: high pressure helps the condensation of water dipoles to the activated complex. Thus, $|\Delta H_s^*|$ and $|\Delta S_s^*|$ increase with pressure.

Equation (14) explains the variation of $|\Delta H_s^*|$ with temperature. On the r.h.s. of Eq.(14), the absolute value of the bracketed quantity decreases with temperature because of the factors n and ln[H2O] in it. But, the decrease of the bracketed quantity is overpowered by the RT2 outside the brackets. Thus $|\Delta H_s^*|$ increase with temperature.

The above fact is physically understood in the following way. Although the condensation of water dipoles decreases with temperature, the condensation at a high temperature accompanies $|\Delta H_s^*|$ which is larger than at a low temperature because the water dipoles have more kinetic energy than at a low temperature.

The value of $|\Delta H_s^*|$ increase with water content (Table 5). This is also clear from Eq.(14), where n increase with water content as we have already pointed out (see n values in Table 2 and Fig. 2). The increase of n values with water content is caused in turn by longer extention of the critical bond and more charge separation in 10% water content than in 5% as we proposed (see Fig. 4).

The behavior of $|\Delta S_s^*|$ completely parallels that of $|\Delta H_s^*|$. Thus the behavior of $|\Delta S_s^*|$ is explained in a similar way with $|\Delta H_{s}^{*}|$.

Comparing Eq.(16) with (14), one notes that the first term on the right-hand-side of Eq.(16) is $\Delta H_s^*/T$ [see Eq.(14)] which is a negative quantity, and the second term is a positive term. But the latter term contribution is very small compared to that of the former term, thus ΔS_s^* becomes negative. From the similarity of the expressions of ΔH_s^* and ΔS_s^* [Eqs.(14) and (16)], one may understood the similar behaviors of the two quantities.

D. Variation of ΔH_c^* and ΔS_c^* with pressure, Temperature and Water Content. The quantities, ΔH_{ϵ}^* and ΔS_{ϵ}^* , are expressed by the following equations as previously mentioned:

$$\Delta H_c^* = \Delta H_e^* + \Delta H_s^*$$

$$\Delta S_c^* = \Delta S_e^* + \Delta S_s^*$$
 (19)

The variations of ΔH_c^* and ΔS_c^* with P, T and water content are explained by using Eq.(19) and by the following phenomenological relations: $\Delta H_{\epsilon}^* > |\Delta H_{\epsilon}^*|$ and $\Delta S_{\epsilon}^* < |\Delta S_{\epsilon}^*|$, where the behaviors of $|\Delta H_s^*|$ and $|\Delta S_s^*|$ were considered previously.

The quantity ΔH_{ϵ}^* is independent of P. Since $\Delta H_{\epsilon}^* > |\Delta H_{\epsilon}^*|$, and since the latter increases with P, the ΔH_c^* decreases with pressure in agreement with experiment (Table 5). In Eq.(19), ΔS* is independent of P, and is a positive quantity whereas ΔS_{ϵ}^{*} and ΔS_{ϵ}^{*} are negative. Since $\Delta S_{\epsilon}^{*} < |\Delta S_{\epsilon}^{*}|$, and since the latter increases with P, the ΔS_c^* increase with pressure, this also agrees with experiment (Table 6).

Concerning to the temperature effect on ΔH_{ϵ}^{*} , both ΔH_{ϵ}^{*} and $|\Delta H_s^*|$ increase with T, but the increase in ΔH_s^* overcomes that of $|\Delta H_s^*|$. Since $\Delta H_s^* > |\Delta H_s^*|$, the ΔH_s^* increase with temperature (see Table 5). Next we consider the temperature effect on ΔS_c^* . In Eq.(19), both ΔS_c^* and $|\Delta S_c^*|$ increase with temperature (see Table 6). But the former increase overpowers the latter increase, and since $\Delta S_c^* < |\Delta S_c^*|$, the $|\Delta S_c^*|$ decreases with T.

The quantity ΔH_c^* increases with water content (Table 5). This fact is explained as follows. As previously explained, $|\Delta H_c^*|$ increases with water content, while ΔH_c^* also increases. But the latter increase overcomes the former. Thus, from Eq.(19) and the relation $\Delta H_c^* > |\Delta H_c^*|$, the quantity ΔH_c^* increases with water content. The decrease of ΔS_c^* with water content (Table 6) is similarly explained; in Eq.(19) both ΔS_c^* and $|\Delta S_c^*|$ increase with water content, but the former increase overcomes the latter increase keeping the relation $\Delta S_c^* < |\Delta S_c^*|$, as a result, $|\Delta S_c^*|$ decreases with water content.

E. Hydration Numbers and Rate Constants. We noted that $n = (n^+ + n^-) - j$ [see Eq.(2a)]. Previously it was mentioned that n is independent of pressure, but decreases with temperature. We also found that n is increases with water content. The hydration number j for the ground state molecule of \varnothing COCl is considered to be constant independent of water content at a given pressure. Thus, the increase in n in high water content is due to the increase in $(n^+ + n^-)$ in agreement with our model (see Figure 4).

According to Table 2, the k_* value for 10% water content is larger than that for 5% water content by a factor of 25 to 83. This fact is explained below by taking an example. The ΔG_*^* for reaction (1) is expressed by $\Delta G_*^* = \Delta H_*^* - T\Delta S_*^*$. This equation is applied to the cases of 5% and 10% water contents at 15°C. The data of ΔH_*^* and ΔS_*^* are taken from Table 5 and Table 6, respectively. Thus the ratio of $k_*(5\%)/k_*(10\%)$, was calculated by the following equation:

$$k_e(5\%)/k_e(10\%) = \exp\{(RT)^{-1} \left(-\Delta H_e^*(5\%) + \Delta H_e^*(10\%) + T \left(\Delta S_e^*(5\%) - \Delta S_e^*(10\%) \right) \right\}$$
(20)

The value calculated from Eq.(20) is equal to 81.75, and it is in a good agreement with experimental value of $5.78\times10^{-10}/0.07\times10^{-10}=82.57$ from Table 2.

Next, the ratio of $k_c(5\%)/k_c(10\%)$ is given by the following equation:

$$k_c(5\%)/k_c(10\%) = \exp\{(RT)^{-1} \left\{ - (\Delta H_c^*)_{5\%} + (\Delta H_c^*)_{10\%} + T (\Delta S_c^*)_{5\%} - T (\Delta S_c^*)_{10\%} \right\}$$
(21)

where, $\Delta G_c^* = (\Delta H_c^*) - T(\Delta S_c^*)$. From Tables 5 and 6, the corresponding data for ΔH_c^* and ΔS_c^* at one bar and 15°C are taken, and are introduced to Eq.(21), and the ratio is calculated to be 0.468; this value completely agrees with experimental value of $0.84 \times 10^{-4}/1.82 \times 10^{-4} = 0.468$ from Table 2.

The ratio (k/k_c) at one bar, 15°C and 5% water content is calculated from the following equation:

$$(k_c/k_e)_{5\%} = \exp\{(RT)^{-1} (-\Delta H_c^* + \Delta H_e^* + T (\Delta S_c^* - \Delta S_e^*))_{5\%} \}$$
 (22)

by using the value of ΔH_s^* (= ΔH_c^* – ΔH_c^* , Table 5) and ΔS_s^* (= ΔS_c^* – ΔS_c^* , Table 6), and it was found to be 1.47×10^5 , which is in a good agreement with experimental value, $8.40 \times 10^{-5}/5.78 \times 10^{-10} = 1.45 \times 10^5$, from Table 2.

F. Constancy of k_r with Pressure. We have shown that k_r does not vary with pressure (see Fig. 2). Marshall also presented various cases in which k_r is nonvariable with respect to pressure. It was already mentioned that the constancy of k_r yields $\Delta V_r^* = 0$ at constant temperature [see Eq.(9b)]. We

consider the physical meaning of $\Delta V_{\epsilon}^* = 0$ below.

The quantity ΔV_{\bullet}^{*} is represented by the following equation:

$$\Delta V_{\bullet}^{*} = [V_{0}[MA(aq)] + \delta V_{\bullet}^{*}(MA) - \delta V_{0}(aq)] - \delta V(n H_{2}O) - V_{0}[MA(aq)]$$
(23a)

In Eq.(23a), MA(aq), represents $\varnothing COCl(Aq)$, $V_o[MA(aq)]$ is an intrinsic volume of MA(aq), $\delta V_o^*(MA)$ is the volume change due to the critical bond extension of M-A, $-\delta V_o(aq)$, represents the volume contraction due to the redistribution of the hydrated water (aq), and $-\delta V(n H_2O)$ represents the volume contraction due to the loose attachment of $n H_2O$ to the activated complex from the free state of water. From Eq.(23a),

$$\Delta V_e^* = \delta V_o^* (MA) - \delta V_o (aq)_s - \delta V (n H_2O) = 0$$
 (23b)

i.e., the volume increase due to the critical bond extension, δV_{\bullet}^* (MA), equals the volume contraction due to $\delta V_{\bullet}(aq)$, and $\delta V(n H_2O)$. Since $\Delta V_{\bullet}^* = 0$, the following relations results:

$$\Delta G_e^* = \Delta A_e^* = \Delta H_e^* - T \Delta S_e^* \tag{23c}$$

and since ΔG_{\star}^{*} is pressure independent, the pressure independency of ΔH_{\star}^{*} and ΔS_{\star}^{*} at constant temperature follows immediately from Eq.(23c) as experimentally found.

- G. SN₁ or SN₂. The criteria for deciding the SN₁ or SN₂ nature for a solvolysis, which are reported in the literature are summarized in the following.
- (1) The first criterion comes from the activation parameters, i.e., the SN₁ mechanism is predominant when ΔH_1^{μ} value is large and $|\Delta S_1^{\mu}|$ value comparatively small, otherwise the SN₂ mechanism is dominant¹⁰.
- (2) The second criterion uses the solvent effect; The SN₁ mechanism superior to the SN₂ mechanism when the m value of the Grunwald-Winstein plot¹⁷ is larger than 0.6 and when the m value is less than 0.5, the reverse is true.
- (3) The third criterion depends on the number of water molecules(n) participating in the activated complex; The SN_1 mechanism is more influential than the SN_2 in the case when the n is large (*i.e.*, 6 or 7), if n is small (*i.e.*, 1 or 2) the reverse is the case¹⁸.
- (4) The fourth criterion is based on the substituent effect to the reactant; The SN₁ mechanism is more favourable than the SN₂ when the Hammett plot¹⁹ is concave or convex, whereas the SN₂ is predominant if the plot yields a straight line.

In the above, each of the criteria has its own merit in deciding the SN₁ and SN₂ mechanisms. In the following, however, we propose our own criteria:

- (1) If $|\Delta H_s^*|$, $|\Delta S_s^*|$, ΔH_s^* and ΔS_s^* are comparatively large the SN₁ type is predominant.
- (2) If the above quantities are comparatively small especially when $\Delta S_c^* < 0$, then the SN₁ type is superior to the SN₁ type.

For deciding the largeness or smallness of the activation parameters, it is recommended to determine k_c and k_r at several water contents of a mixture solvent under pressure. Since the SN₁ mechanism appears generally at high water content, it is fairly easy to decide which mechanism is dominant.

From our criteria, the solvolysis of benzoyl chloride which we studied is mainly a SN₁ type reaction while the SN₂ mechanism appears to occur with the SN₁ type when the water content of the mixture solvent is small. This is evidenced by the appearance of the case of ΔS_{c}^{*} <0 at 15°C and 5 wt% water

content (see Table 6). Although we need more experimental data at various water content, in fovor of our criteria, it can be said that our criteria are very simple and are trustworthy compared to the ones proposed so far.

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Effects of Hydration and Metal Ions on the Conformation of Daunomycin

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Daunomycin, an anthracycline antibiotic, has been found to inhibit virus multiplication and shows considerable activity against tumors. Its activity may be varied by conformational changes of daunomycin. The conformational changes are come from the pucker of D-ring and variation of environments. We have carried out conformational analyses by using empirical potential function. We found that when daunomycin is hydrated or bound to Mg^{2*} ion, the minimum conformer of each state is altered from α conformer to β conformer through the pathway having four local minima. Our calculated results are in good agreements with those of X-ray crystallography and biological experiments, in which metal ion inhibits the binding of daunomycin to DNA.

Introduction

The daunomycin is the anthracycline antibiotic with an amino sugar group. It is thought that the interference with DNA synthesis and function occurs via an intercalation of the anthracycline chromophore between base pairs in duplex DNA^{1,2}. Since small changes in the drug structure may lead to marked changes in the biological activity^{2,4}, the conformation study around the ether linkage connecting the chromophore and amino sugar is found to be very important^{5,7}.

Several workers have studied the conformation of daunomycin according to potential energy calculations⁵⁻⁷ as well as the X-ray crystallography⁸⁻¹⁰. However, previous reports have shown conflicting results in comparing the conformation of minimum energy with those of the crystals^{5.6.11}. The conformation of daunomycin bound to DNA may be nearly identified with the crystal structure of daunomycin itself^{4.5.10}. However

NMR data in aqueous solution indicate that the conformation of daunomycin may differ from the preferred conformation found in the crystal form¹¹.

Several different conformations come from the pucker of cyclohexene ring (D-ring) within daunomycin. Prominent differences are that there is a hydrogen bond between C7 oxygen and C9 hydroxyl group (α conformer) or the amino sugar becomes oriented equatorially rather than axially (β form)^{4,5,11}.

The pucker of D-ring is occurred via the variation of environments around the daunomycin. That is, the internal hydrogen bond which may stabilize α conformer can be broken by water molecules in aqueous solution⁵.

The conformational analysis of daunomycin could be performed by examining relative dispositions of the sugar group, anthracycline chromophore, and functional groups bound to the phosphate backbone of DNA in various environments. Previous conformational analyses have centered on \emptyset_3 and \emptyset_4