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Substrate-Nucleophile Association in the Finkelstein Reaction System in Dipolar Aprotic Solvent. Formation of Complex between Substituted Chloromethanes and Halide Ion in Acetonitrile*

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Substrate-nucleophile association was found between substituted chloromethanes ($\mathrm{ArXCH_2Cl}$: X=NONE, S, SO, $\mathrm{SO_2}$, and CO) and halide ion ($\mathrm{Cl^-}$, $\mathrm{Br^-}$, and $\mathrm{I^-}$) in dipolar aprotic solvent. The equilibrium constant (K), limiting shift (Δ_c), the enthalpy of formation (ΔH°), and the entropy of formation (ΔS°), for complexing were determined by NMR measurement. The measurement of spin-lattice relaxation time (T_1) gave an information on the conformation of this complex. Halide ion seems to locate closest to α-methylene protons at the site of potential S_N2 reaction.

In the course of studies on the symmetrical Finkelstein reaction in a dipolar aprotic solvent,[1,2] the present authors found the specific interaction between a strong nucleophile and a substrate (substituted chloromethanes).

$$\mathrm{ArXCH_2Cl} + \mathrm{Y^-} \overset{K}{\rightleftharpoons} \mathrm{ArXCH_2Cl\cdot Y^-} \qquad (1)$$

Ar = Phenyl and substituted phenyl
X = NONE, S, SO, $\mathrm{SO_2}$, and CO
Y = Cl, Br, and I
$\mathrm{Y^-}$ was used in the form of
tetraalkylammonium salt ($\mathrm{R_4NY}$; R=ethyl or butyl).

The interaction was observed as a low field shift of the absorption in a PMR spectrum of substrate, on the addition of nucleophilic anion to the solution of the substrate in dipolar aprotic solvent. Martin, Hayami and Lemieux reported the formation of an anion-substrate complex for β-glycopyranosyl derivatives.[3] Green and Martin extended the study to trihalomethanes and other substrates.[4] They attributed such an interaction mainly to hydrogen bonding. Since then, such hydrogen bonding equilibria have been studied extensively between various nucleophilic anions and hydrogen donors. Typical examples were found in the interaction of carboxylic acids[5] or phenols[6] with various anions.

The most important feature of the present study lies in the fact that the complex formation is operative under the same conditions where the symmetrical Finkelstein reaction with radioactive chloride ion actually proceeds.

$$\mathrm{ArXCH_2Cl} + {}^*\mathrm{Cl} \xrightarrow{k} \mathrm{ArXCH_2{}^*Cl} + \mathrm{Cl^-} \qquad (2)$$

In the present study, thermodynamic aspects of the complex formation are described. Measurements of the proton spin-lattice relaxation time were made to indicate the partial freezing of the intramolecular rotation about the potential S_N2 reaction center.

Experimental

Materials. Acetonitrile was distilled five times from $\mathrm{P_2O_5}$ and once from $\mathrm{K_2CO_3}$ initially, and finally distilled with no reagent added. The dry solvent was stored in a dry box.

Substituted chloromethanes[7] were synthesized according to the standard procedure.

Tetraalkylammonium Salts: Tetraalkylammonium halides were prepared by the reaction of the corresponding alkyl halides and trialkyl amines in acetonitrile.[3] Tetraethylammonium perchlorate was prepared by the reaction of tetraethylammonium bromide and perchloric acid. Immediately before each measurement, all the salts were dried under reduced pressure over $\mathrm{P_2O_5}$ at the refluxing temperature of toluene (or benzene for perchlorate) for 2 h.

Proton Magnetic Shift Measurement. An aliquot of the stock solution of substituted chloromethane (0.1 mmol) and TMS in acetonitrile was placed in volumetric tubes (1 ml) containing ammonium salts (0.2—1.2 mmol). The solutions were made up to the mark, and then were transferred to the NMR sample tubes. All the samples were prepared inside a dry box. The PMR spectra were measured in an internal lock mode for the solvent acetonitrile, with a JEOL PS-100 spectrometer operating at 100 MHz. The line positions were measured to 0.1 Hz by reading the frequencies at each resonance of substrate and the internal standard, TMS, with a built-in frequency counter at least four times and averaging the results.

Analysis of PMR Shift vs. Concentration. Equilibrium constant, K, and limiting shift of the complex, Δ_c, were determined by means of Scott's modification of the Benesi-Hildebrand equation,[8,9] assuming only 1 : 1 complex of substrate and halide ion. In this treatment the degree of dissociation of ammonium salt was assumed to be constant in the concentration range of measurements.[10,11] Analysis was repeated until a self-consistent set of values was obtained. It was carried out automatically on the programmable calculator, Canon SX-110. The use of PMR measurement is an authorized method for the study of hydrogen bonding interaction, being essentially similar to that given by Martin and coworkers.[3]

Measurements of Spin-lattice Relaxation Time (T_1). Spin-lattice relaxation curves of protons were obtained on a JEOL PS-100 NMR spectrometer equipped with a pulse Fourier-transform unit (PFT-100) and a spectrum computer (EC-100), by application of 180°-t-90° pulse sequences at 100 MHz. The spin-lattice relaxation time (T_1) was deduced by the least-squares approximation of the observed value of $I_{(t)}$ to $I_0[1-2\exp(-t/T_1)]$, where $I_{(t)}$ is longitudinal magnetization at time t, and I_0 is the equilibrium magnetization.[12] Measurements were carried out with two samples for each series of substituted chloromethanes, the standard acetonitrile solution of the substrate (0.1 M), and a solution in which the appropriate amount of tetraethylammonium chloride

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was added to the standard solution.

Since the equilibration is very fast as compared with the $1/T_1$ of the protons in both the free and the complexed substrate, the observed $T_1(T_1^{\text{obsd}})$ in the present case can be expressed as the weighted means.[13)]

$$1/T_1^{\text{obsd}} = f^{\text{c}}/T_1^{\text{c}} + f^{\circ}/T_1^{\circ} = f^{\text{c}}R_1^{\text{c}} + f^{\circ}R_1^{\circ}, \tag{3}$$

where f^{c} and f° denote the fractions, T_1^{c} and T_1°, the relaxation time, and R_1^{c} and R_1°, the rate of relaxation of complexed and uncomplexed species, respectively. Since f^{c} and f° can be calculated from the equilibrium constant (K), the values of R_1^{c} are easily deduced. The rotational correlation time (τ_{c}) can be calculated from R_1 by means of

$$R_1 = (3/2)\hbar^2\gamma_{\text{H}}^4\tau_{\text{c}}/r_{\text{HH}}^6, \tag{4}$$

where $\hbar$ is the Planck constant divided by 2π, γ_{H} is the gyromagnetic ratio of proton, and r_{HH} is the distance between neighboring protons.[14)] The effect of complexing on the intramolecular rotation is sharply reflected on τ_{c}. $\tau_{\text{c}}^{\text{c}}$ and τ_{c}° denote the rotational correlation time of the complexed and the uncomplexed species, respectively.

Results and Discussion

On addition of tetraalkylammonium halide to the acetonitrile solution of substituted chloromethanes, the PMR absorption showed low field shift. The amount of shift of each proton was analyzed by the Scott modification of the Benesi-Hildebrand equation,[3)] which gave a good linear relationship in each case. α-Methylene protons of (arylsulfinyl)chloromethanes, which appear as AB quartet in acetonitrile solution, exhibit a different response on complexing; the proton in a higher field showing apparently a larger shift (Fig. 1). The difference in the response was also substantiated in the measurement of spin-lattice relaxation time (T_1). On addition of chloride ion, the rate of relaxation became higher at the proton lying in the higher field.

Effect of the Ammonium Salts. The effect of tetraalkylammonium salts on the formation of the complex was investigated by using (*p*-chlorophenylsulfonyl)chloromethane as substrate, which showed a low reactivity in S_N2 reactions and gave no detectable amount of the substitution product with various halide ions under the conditions of the PMR measurement. The results are given in Table 1.

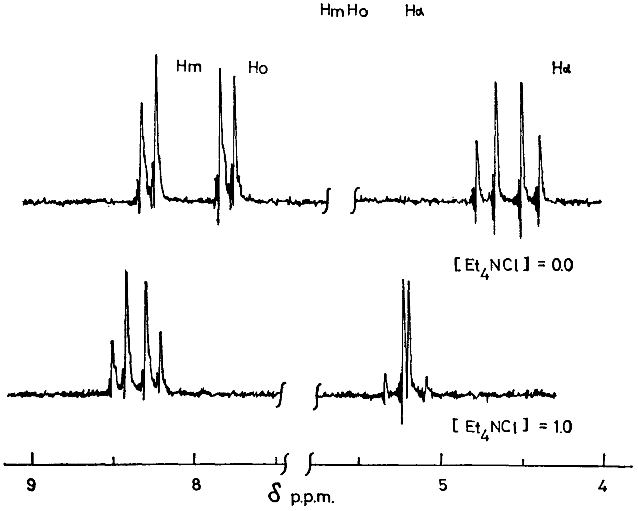

Fig. 1. Change of pmr spectra of (*p*-nitrophenylsulfinyl)chloromethane in acetonitrile after addition of TEACl.

Since tetraethylammonium perchlorate showed essentially no ability in the formation of complex, and the other salts studied gave rise to significant changes in the chemical shift of the substrate, it is understood that the cation portion of the ammonium salts plays no essential role in the change of PMR shift, and that the anion portion eventually controls these equilibria.

The most electronegative chloride ion forms a more stable complex than other halide ions (Br^- or I^-) do. The results suggest that the interaction is similar to that studied by Martin and coworkers,[3,4)] and that it might be of hydrogen bonding. The present results also suggest that such a phenomenon is general for substances with "acidic" proton(s) as were the cases with certain β-glycopyranosyl derivatives and with trihalomethanes.

Tetraethylammonium bromide and tetrabutylammonium bromide differ in the formation constant of the complex (K), although these salts have bromide ion in common. The difference can be ascribed to the difference in the ion pair dissociation of the salt in the organic solution.[15)] Tetrabutylammonium iodide is apparently a more effective hydrogen bond acceptor than expected from the basicity of iodide ion. This might also be ascribed to the ion pairing phenomena of the ammonium iodide.[15)] However, lack of information on the behavior of the ammonium salts in high concentrations allows no further discussion.

Effect of the Solvent. The substituted chloromethanes form a complex with the halide ion, not only in acetonitrile but also in other dipolar aprotic solvents (DMSO or DMF). However, addition of a protic solvent (methanol) to the solution in acetonitrile retards the substrate-anion complex formation (Table 2). This can be explained in terms of the competitive hydrogen bonding between a protic solvent and the halide ion.[16)] Methanol exhibits a strong tendency to undergo hydrogen bonding association with chloride ion.[17)]

PMR Shift. Equilibrium constant (K) and the limiting shift of the complex (Δ_{c}) for *p*-nitrophenyl derivatives of substituted chloromethanes, with tetraethylammonium chloride as hydrogen bond acceptor,[18)]

TABLE 1. EFFECT OF TETRAALKYLAMMONIUM SALTS ON THE FORMATION OF COMPLEX
[p-Cl-Ph-SO_2-CH_2Cl + R_4NX][a)]

R_4NX		K
R	X	(M^{-1})[b)]
C_2H_5	Cl	0.820
C_2H_5	Br	0.358
n-C_4H_9	Br	0.555
n-C_4H_9	I	0.711
C_2H_5	ClO_4	0

Throughout this paper $1\ \text{M} = 1\ \text{mol dm}^{-3}$, $1\ \text{cal}_{\text{th}} = 4.184\ \text{J}$, $1\ \text{Å} = 0.1\ \text{nm}$.

a) In acetonitrile, at 25 °C. b) Errors estimated to be within 0.005.

Table 2. Effect of the protic solvent (MeOH) on the formation of complex [p-NO$_2$-Ph-CH$_2$Cl + TEACl][a)]

MeOH	K (M^{-1})[b)]
0	0.258
0.061	0.232
0.123	0.188
0.245	0.141
0.491	0.084

a) In acetonitrile, at 32 °C. b) Errors estimated to be within 0.005.

Table 3. Summary of the formation of complex between substituted chloromethanes and TEACl in acetonitrile [p-NO$_2$-Ph-X-CH$_2$Cl + Cl$^-$][a)]

Substrate (-X-)	Δ_c(*meta*)	Δ_c(*ortho*) (ppm)[b)]	Δ_c(α-CH$_2$)	K[c)] (M^{-1})	$\rho(K)$
NONE	−0.220	−0.681	−0.943	0.258	0.63
S	−0.089	−0.584	−1.229	0.493	0.59
SO	−0.197	−0.547	−1.178[d)] −1.190	1.190	0.61
SO$_2$	−0.148	−0.441	−1.506	1.282	0.51
CO	−0.241	−0.541	−1.012	0.403	0.52

a) At 32 °C. b) Errors estimated to be within 0.004 ppm. c) Errors estimated to be within 0.005. d) Proton at the higher field gives a larger Δ_c value (Fig. 1).

are summarized in Table 3. As the substituent becomes more electron-withdrawing, the association seems to prevail. This is also in line with the view that the principal cause of this interaction should be hydrogen bonding to the α-methylene protons.[19)]

The changes of chemical shift can be attributed mainly to the effect of electrostatic field originating at halide ion. The electrostatic field at the hydrogen atom is a function of the anion–hydrogen distance, and the limiting shift (Δ_c) is a function of distance and the angle. This can be seen from the simple approximation in terms of Buckingham's equation for the electrostatic field produced by the point charge:[20)]

$$\Delta_c = -A(1/r_{HX}^2)\cos\theta - B(1/r_{HX}^4), \tag{7}$$

where r_{HX} is the distance from the anion center to the hydrogen nucleus, and θ is the angle between the C–H and H–anion vector.

Thus, the location of the halide ion can be inferred from the value of Δ_c. In each compound the absolute values of Δ_c decrease in the order α-CH$_2$≫*ortho*>*meta*, suggesting that the chloride ion is located in a close neighborhood of α-methylene protons.

Linear Free Energy Relationship. For equilibrium constant of the complex formation (K), a linear Hammett relationship holds in every series of compounds, the positive ρ values being obtained. The results are given in Table 3. Positive ρ values indicate that substituted chloromethanes act as a hydrogen bond donor. Electron-withdrawing substituents enhance the acidity and the donor capacity of a proton.

Table 4. Arrhenius parameters for the formation of complex [p-NO$_2$-Ph-X-CH$_2$Cl + Cl$^-$]

X	$\Delta H°$ [a)] (kcal mol^{-1})	$\Delta S°$ [b)] (eu)
NONE	−4.88	−18.6
S	−1.75	−7.19
SO	−1.40	−4.18
SO$_2$	−1.22	−3.82
CO	−5.31	−21.0

a) Errors estimated to be within 0.5 kcal mol^{-1}. b) At 20 °C. Errors estimated to be within 2.0 eu.

Arrhenius Parameters for the Formation of Complex. Equilibrium constants were determined at temperatures 0—30 °C. Arrhenius parameters of formation for the anion-substrate complex are given for p-nitrophenyl derivatives as the representative in Table 4. Both the enthalpy of formation ($\Delta H°$) and the entropy of formation ($\Delta S°$) give negative values, which are in a reasonable range for the hydrogen bonding equilibria.[17,19)] Negative values of $\Delta H°$ indicate that a stabilization can be attained to some extent by complex formation. The order of stabilization ($-\Delta H°$), [$-\Delta H^\circ_X$ for ArXCH$_2$Cl: $-\Delta H^\circ_{SO_2} < -\Delta H^\circ_{SO_2} < -\Delta H^\circ_S < -\Delta H^\circ_{NONE} < -\Delta H^\circ_{CO}$] is not in agreement with the order of the magnitude of K. It is in contrast to the fact that in most hydrogen bonding equilibria there is a coincidence between the order of magnitude of K and of $-\Delta H°$.[21)] Negative values of $\Delta S°$ are found as is often the case with a bimolecular association. In the present case, the stabilization of the complex is counterbalanced by the entropy loss, giving rise to a K smaller than unity or close to unity. As will be suggested later from the study of proton relaxation time, it seems that the freezing of intramolecular motion plays an important role in decreasing $\Delta S°$.

Effect of the Complex Formation on Proton Spin-lattice Relaxation Time (T_1). Recently, T_1 measurements have been applied to the investigation of interactions between or within organic molecules.[22,23)] The T_1 value is very sensitive to the change of environmental factors. In the present case T_1 gives unique indication of the interaction between the anionic nucleophile and the substrate.

Each proton of substituted chloromethanes shows an appreciable increase in relaxation rate ($1/T_1 = R_1$) on addition of the nucleophilic anion (Cl$^-$). Perchlorate ion gives no significant effect on T_1, reflecting its poor ability as a hydrogen bond acceptor (Table 5). This suggests that the influence of the increasing viscosity of the acetonitrile solution caused by the addition of ammonium salt is not detrimental under the present experimental conditions. It has also been established that the chlorine atom (from tetraethylammonium chloride), with its small gyromagnetic moment, can give no noticeable contribution to the nuclear magnetic relaxation.[25,26)] Thus, one possible mechanism remains operative in altering T_1 on complexing. That is the change of the rotational correlation time (τ_c), caused by the retardation of the intramolecular rota-

TABLE 5. EFFECT OF COMPLEXING ON T_1 a)

X b)	R_1°(CH$_2$) c) R_1°(*meta*)	R_1^{c}(CH$_2$) c) R_1^{c}(*meta*)	τ_c°(CH$_2$) d) τ_c°(*meta*)	τ_c^{c}(CH$_2$) d) τ_c^{c}(*meta*)	$\tau_c^{c}/\tau_c^{\circ}$(CH$_2$) $\tau_c^{c}/\tau_c^{\circ}$(*meta*)
NONE	0.12_2	0.33_9 f)	4.5_4	$12._6$	2.7_8
	(0.12_8) e)	(0.31_3)	(4.7_7)	$(11._7)$	(2.4_5)
	0.06_2	0.26_2	$17._3$	$70._7$	4.0_9
	(0.06_5)	(0.24_0)	$(18._2)$	$(67._0)$	(3.6_9)
S	0.18_3	1.15_7	6.7_9	$43._0$	6.3_3
	0.07_0	0.13_1	$19._6$	$36._6$	1.8_6
SO	0.26_0	0.78_8 g)	9.6_9	$29._3$	3.0_2
	0.07_3	0.09_2	$20._4$	$25._7$	1.2_6
SO$_2$	0.23_6	0.64_9	8.7_8	$24._1$	2.7_4
	0.07_5	0.08_8	$21._0$	$24._4$	1.1_6
CO	0.40_5	1.93_6	$15._1$	$72._0$	4.7_7
	0.05_8	0.34_1	$16._2$	$95._0$	5.8_6

a) At 25 °C. b) *p*-NO$_2$-Ph-X-CH$_2$Cl. c) s^{-1}. d) ps. e) Values in parentheses are the data where TEAClO$_4$ (0.8 M) was added to the standard solution to detect the influence of viscosity. f) For α-d_1, at 30 °C, $R_1^{\circ}(\mathrm{CHD})/R_1^{\circ}(\mathrm{CH_2})=0.02^2/0.09^4=0.23^4$, $R_1^{c}(\mathrm{CH_2})/R_1^{\circ}(\mathrm{CH_2})=3.8_3$, $R_1^{c}(\mathrm{CHD})/R_1^{0}(\mathrm{CHD})=4.3_5$. g) Proton at the higher field gives greater R_1^{c}. $R_1^{c}(\mathrm{CH_2})=\{R_1^{c}(\mathrm{CH_2}-l)+R_1^{c}(\mathrm{CH_2}-h)\}/2=\{0.417+1.158\}/2$; CH$_2$$-h$ and CH$_2$$-l$ denote methylene proton at the higher field and the lower field (*cf.* Fig. 1).

tion in the complexed substrate.[27]

For the relaxation of the α-methylene protons of substituted chloromethanes, only a single H–H distance corresponding to geminal protons should be considered, since aromatic protons are situated in too remote a position to contribute significantly to the relaxation of α-methylene protons (the interaction contributing to the spin-lattice relaxation of protons diminishes rapidly with increase in the interproton distance, as expressed by Eq. 4). The postulate is verified by the deuteruim labelling experiment. Substitution of one of the methylene protons with deuterium causes a striking increase in T_1.[26] Similarly, for relaxation of the protons on benzene ring (*para* substituted), only a single H–H distance between the nearest neighbor, vicinal protons, needs to be considered.

Consequently, as a first approximation, T_1 can be correlated with rotational correlation time (τ_c), as expressed by Eq. 4, where 1.78 Å is taken to be the quantity r_{HH} for α-methylene protons and 2.49 Å for vicinal protons on benzene ring. Variations in the proton spin-lattice relaxation rate ($R_1=1/T_1$) and τ_c of α-methylene proton and meta proton on complexing are shown for substituted chloromethanes having a *p*-nitro group on the phenyl ring in Table 5. The postulate seems to be reasonable, since the τ_c° value calculated is shoter at a more mobile α-methylene group than at a less mobile aromatic ring.

Change of T_1 (or τ_c) furnishes additional evidence that nucleophilic chloride ion interacts with the chloromethanes. The substrates studied can be classified into two groups, one group of compounds (X=S, SO, SO$_2$) which show little change in τ_c(*meta*) but a significant change in τ_c(CH$_2$), and the other (X=NONE, CO) in which both the ring proton and the α-methylene proton show significant change in the rate of relaxation. Such tendency is in line with that of the enthalpy and entropy of the formation of complex and with the temperature coefficient of the limiting shift ($\partial\Delta_c/\partial T$).[28]

The former group shows small negative enthalpy and entropy of formation of the complex, their limiting shift being hardly affected at all by the change in temperature.[28] This tendency of the parameters suggests that the nature of the association is of hydrogen bonding. On complexing, the substrate moiety becomes "rigid", the intramolecular rotation about the chloromethyl group being frozen considerably to bring about a common τ_c^{c} for both the ring proton and the methylene proton. Such a τ_c^{c} may correspond to the molecular motion of the complex as a whole. In this class of compounds, τ_c(*meta*) may be taken as a measure of the molecular motion of the substrate as a whole mass, since the rotation around the pheyl ring—X axis is considered to have little effect upon the relaxation of both the *ortho* and/or *meta* proton.[27]

Thus, a reasonable explanation can be presented for the compounds of the former group. The data indicate that the important part of the loss of entropy can be attributed to the freezing of the internal rotation at the complexed species.

The latter group of compounds (X=NONE, CO) show an extensive change in τ_c (and/or R_1) for both the α-methylene and the ring proton(s). The two compounds show significant enthalpy and entropy of formation of the complex, their limiting shifts showing a significant dependency on temperature. The behavior implies that some interaction other than hydrogen bonding can be operative in the complexing of these substrates.[19,20a,20b]

(*p*-Nitrophenyl)chloromethane shows a change in τ_c(CH$_2$) comparable to that found for the former group of compounds, however, change in τ_c(*meta*) is anomalously large. A tentative explanation is that some other kind of relaxation mechanism is operative for the ring proton(s), the former proposition for the relaxation being not valid for the complex derived from this substrate. Another explanation is that the complexing brings about a particular conformation in which another dipole-dipole interaction is possible between the α-methylene and the ring proton(s). A

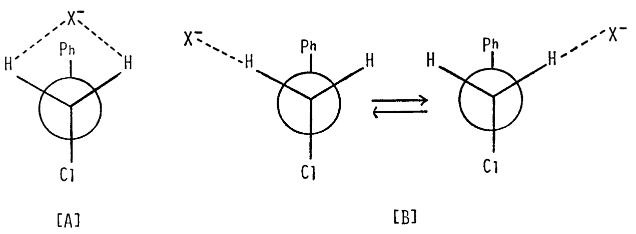

Fig. 2. Modes of coordination of halide ion to substituted chloromethanes.

reasonable change in $\tau_c(CH_2)$ for the deuterated substrate (α-d_1) seems to suggest the first possibility. An interaction between the chlorine and the phenyl ring may be responsible for the additional relaxation.

2-Chloro-1-(*p*-nitrophenyl)ethanone indicates an extensive interaction with chloride ion. Characteristic implication for this compound is that an uncomplexed substrate shows a common τ_c° at both the α-methylene and the ring proton. This suggests that intramolecular rotation is already hindered about the chloromethyl moiety. On the formation of the complex, the substrate seems to become "rigid", otherwise some additional mechanism seems to be operating. An interaction between the chloride ion and the carbonyl group was suggested in the change of CMR shift caused by the addition of chloride.[29] Such an interaction between the nucleophile and the carbonyl group is postulated in the S_N2 reactions of α-halo ketones.[30]

Mode of complexing. The data obtained seem to be indicative of the array of nucleophile and the substrate moiety in this complex. Changes of chemical shift induced by the formation of the complex (Δ_c) are much larger for α-methylene protons than for aromatic protons. There is an apparent parallelism in the magnitude of the equilibrium constant (K) and the order of the electron deficiency at the α-methylene (K_X for $ArXCH_2Cl$; $K_S < K_{SO} < K_{SO_2}$). It seems that the major site of coordination upon complexing with nucleophile is the α-methylene protons. The changes of T_1 upon complexing also are in line with the view that the major site of coordination is the α-methylene protons.

Two typical modes of coordination of nucleophile to the α-methylene protons, shown in Fig. 2, are (A) a rear side coordination of the nucleophile to the chlorine bonded to carbon, and (B) a rapidly exchanging system, where the nucleophile coordinates to one of the protons at a time, collinear to a C–H bond. These two possibilities are indistinguishable in a rapidly exchanging system as observed in the present PMR studies. However, taking into account the electrostatic repulsion between the halide ion and the chlorine atom on the substrate, (A) seems to be more feasiblle. In the case of the complex formation between β-glucopyranosyl derivatives and a halide ion, the nucleophile seems to be located between the H-1 and the H-5 (and not far from H-3) of the pyranose ring in a similar way to mode (A) in Fig. 2.[3]

It is concluded that the substrate-nucleophile complex should exist in the Finkelstein reaction mixture, and that the nucleophilic anion is located in the close neighborhood of the rear side of carbon to chlorine bond, whichever mode [(A) or (B)] of coordination is operative. Such a coordination resembles that in the transition state of S_N2 reactions. Recent MO calculation also suggests that the deep energy minimum is formed which corresponds to a strong hydrogen bonding interaction in the reaction of monofluoroethane and fluoride ion.[31]

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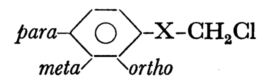

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15) An interpretation for the higher K of the tetrabutylammonium (TBA) bromide or the TBA iodide is to assume the lower degree of ion pair dissociation in the concentrated solution of these two ammonium salts in acetonitrile.

At a low concentration of the salt (<0.3 M), the observed complexing shift is almost equal for both the TBA and tetraethylammonium (TEA) bromide on complexing with chloromethyl sulfones. On increasing the halide ion concentration, the observed down-field shift becomes definitely greater for TEA than for TBA salt. Upon Scott-Benesi-Hildebrand analysis, such a difference gives rise to a larger K for TBA. As the single K (Δ_c) is expected for Br^- ("effective" Br^-), one should assume a lower degree of dissociation for TBA than that for TEA bromide. Similarly, lower degree of dissociation gives rise to high apparent K for the TBA iodide.

Such a treatment is against the ion pair phenomena in a very dilute solution where TBA shows greater dissociation

than TEA does. One of the referees has pointed out this controversy. He suggested that the difference in K can be accounted for by postulating the higher degree of dissociation for TBA and that only the dissociated bromide ion is responsible for the complexing. This treatment seems to be attractive and is sound in principle. However, it should predict much smaller down-field shift for TEA bromide, compared to TBA bromide, especially on going from dilute to concentrated soultion of the ammonium salt. This is just contrary to the case.

For a compromise to both points of view, it could be proposed that the complexing (and necessarily the bimolecular displacement in acetonitrile) proceeds by the intervention of the ion-paired nucleophile instead of the free dissociated halide ion.

However, the controversy remains unsettled.

16) Y. Kondo, T. Kato, and N. Tokura, *Bull. Chem. Soc. Jpn.*, **48**, 285 (1975).

17) a) S. Y. Lam and R. L. Benoit, *J. Am. Chem. Soc.*, **98**, 1156 (1976); b) A. Allerhand and P. von R. Schleyer, *J. Am. Chem. Soc.*, **85**, 1233, 1715 (1963); c) E. M. Arnett, L. Joris, E. Mitchell, T. S. S. R. Murty, T. M. Gorrie, and P. von R. Schleyer, *J. Am. Chem. Soc.*, **92**, 2365 (1970).

18) TEA chloride can easily be purified, and is not very hygroscopic but sufficiently soluble in acetonitrile. With chloride ion, the observed complexing shift is greater then that with other halide ions studied. TEA fluoride attacks most of the substrates. (*cf.* J. Hayami, N. Ono, and A. Kaji, *Tetrahedron Lett.*, **1968**, 1385).

19) One of the referees suggested that value of $\Delta - H^\circ$ for (p-nitrophenyl)chloromethane and for 2-chloro-1-(p-nitrophenyl)ethanone is too large to be ascribed to a simple hydrogen bonding to carbon bound hydrogen. The peculiar behavior of the two compounds is also observed in the change of relaxation rate upon complexing and in the temperature coefficient of the limiting shift ($\partial \Delta_c/\partial T$). The tendencies in $\partial \Delta_c/\partial T$ suggest some interactions other than hydrogen bonding can be operative in the two compounds.[28] (This criterion is circumstantial, however, and one cannot rule out the view that some additional interaction is operative for the three other classes of compounds studied.) However, since the linear Hammett relationship holds in each class of the compounds studied, with respect to the XCH_2Cl group as the reference position, and in view of the analogy to the other example of substrate-nucleophile association reported,[3,4] the hydrogen bonding to the α-methylene proton can be postulated as the major driving force for the association.

20) a) A. D. Buckingham, *Can. J. Chem.*, **38**, 300 (1960); b) N. Muller and R. C. Reiter, *J. Chem. Phys.*, **42**, 326 (1965); c) Ref. 4.

21) D. Gurka and R. W. Taft, *J. Am. Chem. Soc.*, **91**, 4794 (1969).

22) H. H. Mantsch, H. Saito, L. C. Leith, and I. C. P. Smith, *J. Am. Chem. Soc.*, **96**, 256 (1974).

23) R. S. Norton and A. Allerhand, *J. Am. Chem. Soc.*, **98**, 1007 (1976).

24) Slight increase in R_1 was observed by the addition of TEA perchlorate to the solution of the substrate in acetonitrile. However, the change in rate was within experimental error ($\pm 10\%$) inherent in the measurement of T_1 and was ignored.

25) A. Carrington and A. D. McLachlan, "Introduction to Magnetic Resonance," Harper and Row, New York, N. Y. (1967).

26) In a similar way to Eq. 4, direct dipole-dipole interaction of chloride ion contributes to the rate of relaxation as shown by

$$R_1^{\mathrm{H-Cl}} = (15/2)\hbar^2 \gamma_{\mathrm{H}}^2 \gamma_{\mathrm{Cl}}^2 \tau_c / r_{\mathrm{HCl}}^6 \tag{4a}$$

where γ_{Cl} is the gyromagnetic ratio of chlorine and r_{HCl} is the distance between chloride ion and the proton in question.

When one uses the values

$\gamma_{\mathrm{H}} = 26753$ rad s^{-1} G^{-1} (the gyromagnetic ratio of proton)

$\gamma_{\mathrm{Cl}} = 2516$ rad s^{-1} G^{-1} (weighted mean of the gyromagnetic ratio for ^{35}Cl and for ^{37}Cl)

$r_{\mathrm{HH}} = 1.78$ Å (distance between geminal protons of methylene group),

one obtains, from Eqs. 4 and 4a, $R_1^{\mathrm{H-H}}/R_1^{\mathrm{H-Cl}} = 174$ for $r_{\mathrm{HCl}} = 2.5$ Å (This is 0.5 Å shorter than the sum of the atomic and ionic radii, a typical hydrogen bonding distance)[3] and $R_1^{\mathrm{H-H}}/R_1^{\mathrm{H-Cl}} = 3.2_8$ for $r_{\mathrm{HCl}} = 1.3$ Å (the covalent bond distance for hydrogen chloride).

These values suggest that, in the former case, the contribution of the direct interaction of the chloride ion is less than 1% of the contribution of the geminal protons. Even at the covalent bond distance, the contribution of the chloride ion is about 23% of the contribution of the geminal proton. One might assume that, at a reasonable hydrogen bond distance, the direct interaction of the chloride ion plays no important role in the spin-lattice relaxation process.

Results of the study with (p-nitrophenyl)chloromethane-α-d_1 support this postulate. Data from Table 5 [footnote f)] give $R_1^c(\mathrm{CHD})/R_1^c(\mathrm{CH_2}) = 0.26_6$. The significantly slow relaxation of monodeuterated compound indicates that any one of the following conceivable factors does not contribute more than 30% of the spin-lattice relaxation of normal undeuterated substrate: 1) direct dipole-dipole interaction of chloride ion, 2) relaxation by the contribution of the nuclear quadrupole of the chloride ion, 3) long range interaction between methylene proton and the ring protons.

27) The observed rate of relaxation was almost identical, within experimental error, for the vicinal protons on the same phenyl ring. Thus τ_c(*meta*) and τ_c(*ortho*) calculated were almost equal. The intramolecular rotation about the axis of the phenyl-X bond is considered to be ineffective for the relaxation of the ortho and meta proton nuclei. Thus the τ_c(*meta*) can be regarded as a measure of the correlation time of molecular motion as the whole mass. There are examples where difference in τ_c is ascribed to difference in an intramolecular rotation. *Cf.* a) A. Suggett, *J. Solution Chemistry*, **5**, 33 (1976); b) E. Breitmaier, K-H Spohn, and S. Berger, *Angew. Chem. Int. Ed. Engl.*, **14**, 144 (1975).

28) As Muller has pointed out,[20b] some indication is given as to the nature of the solute-solute interaction from the temperature coefficient of $\partial \Delta_c/\partial T$. Generally, when a strong hydrogen bonding is operative, hydrogen bonding shift in PMR is little affected by the changes in temperature. In an association where significant stabilization is found with a significant $\partial \Delta_c/\partial T$, some (additional) interaction other than hydrogen bonding can be operative.

$\partial \Delta_c/\partial T$(ppm deg^{-1}) for $p\text{-}NO_2PhXCH_2Cl$: 1.2×10^{-2} (X=NONE), 2.0×10^{-2} (X=CO), 0.6×10^{-2} (X=S), 0.4×10^{-2} (X=SO), 0.2×10^{-2} (X=SO_2).

29) $Ph^{13}COCH_2Cl$ showed limiting CMR shift 5.0 ppm on complexation with chloride ion while no such a shift was observed for $Ph^{13}CH_2Cl$.

30) J. W. Thorpe and J. Warkentin, *Can. J. Chem.*, **51**, 927 (1973), and references cited therein.

31) J. J. Dannenberg, *J. Am. Chem. Soc.*, **98**, 6261 (1976).