Nucleophilic substitution reactions of phenyl chloroformates

Kyoung Han Yew, Han Joong Koh, Hai Whang Lee and Ikchoon Lee
Department of Chemistry, Inha University, Inchon, 402-751, Korea

Methanolysis and aminolysis of phenyl chloroformates in acetonitrile have been investigated. The rates are slow due to initial-state stabilization by strong resonance electron donation from the phenoxy group. In both reactions the large positive values of $\rho_Y = 0.8$–1.6 and low $\Delta H^{\ddagger}$ and $\Delta S^{\ddagger}$ values show that the transition state is strongly associative with little bond breaking. This mechanism is supported by the relatively large solvent isotope effect, $k_{MeOH}/k_{MeOD} \cong 2.3$–2.5, and by the relatively strong inverse secondary kinetic isotope effect, $k_H/k_D \cong 0.74$–0.94, involving deuteriated aniline nucleophiles, in addition to a negative value of ρ_{XY}. The dependence on aniline basicity, β_X (β_{nuc}) $\cong 0.8$, and the ρ_X values of -2.3 are similar to those corresponding values for the reactions of benzoyl chlorides which have been predicted to react by an associative S_N2 mechanism. These observations are consistent with a concerted displacement mechanism for the methanolysis and aminolysis of phenyl chloroformates.

The mechanism of acyl-transfer reactions has been investigated intensively for many years both experimentally[1] and theoretically.[2] The mechanisms of most of these reactions are, however, still not well established. The solvolysis of acyl halides, RCOX, is believed to proceed either through a direct displacement mechanism (S_N2) or through an associative addition–elimination mechanism involving a tetrahedral intermediate.[3] For acyl halides with a strong electron donating group, R, a dissociative mechanism involving an acylium ion intermediate has also been invoked.[4] The two types of mechanism, S_N2 and stepwise addition–elimination, are also common for the aminolysis of acyl halides. The aminolyses of acetyl chloride, MeCOCl, and methyl chloroformate, MeOCOCl, have been shown to proceed by rate-limiting breakdown of a zwitterionic tetrahedral intermediate, $T^{\pm}$, for weakly basic amines with a change to rate-limiting attack for basic amines.[5]

The aminolysis of benzoyl fluorides in water is reported to proceed by a concerted substitution mechanism, which is, however, likely to be near the mechanistic borderline for a change from a stepwise to a concerted mechanism.[6] Litvinenko and co-workers[7] have also shown that acyl chlorides react with amines by simple second-order kinetics, *i.e.* by an S_N2 type process. In contrast, however, the aminolysis of benzoyl fluorides in non-hydroxylic solvents has been suggested to proceed by rate-limiting breakdown of the tetrahedral intermediate, $T^{\pm}$.[8] In a previous paper, we proposed that the reactions of cinnamoyl chlorides, $YC_6H_4CH{=}CHCOCl$, with anilines, $XC_6H_4NH_2$, in acetonitrile proceed by a stepwise mechanism with rate-limiting breakdown of the tetrahedral intermediate.[9]

In view of the often suggested mechanistic change from rate-limiting breakdown of $T^{\pm}$ to rate-limiting attack by the substituting of a strong electron donating group, R, in the acyl compounds,[10] we conducted kinetic studies on the reactions of phenyl chloroformates (ArOCOCl) with anilines in acetonitrile reaction (1). Our results have indeed suggested such a

$$2XC_6H_4NH_2 + YC_6H_4OCOCl \xrightarrow[25.0\,^{\circ}C]{MeCN} YC_6H_4OCONHC_6H_4X + XC_6H_4NH_3^{+} + Cl^{-} \quad (1)$$

mechanistic change to rate-limiting attack for phenyl chloroformates. We have also carried out kinetic studies on solvolytic reactions of phenyl chloroformates in methanol–acetonitrile mixtures.

Table 1 Rate constants, $k_s/10^3$ s^{-1} for the solvolyses of Y-phenyl chloroformates in MeOH–MeCN mixtures at 25.0 °C

	$k_s/10^3 s^{-1}$				
	Y				
v% MeOH	*p*-OMe	*p*-Me	H	*p*-Cl	*p*-NO_2
100	4.14	4.79	6.94	18.3	134
90	3.87	4.42	6.38	16.4	120
80	3.39	3.87	5.63	14.4	103
70	2.87	3.26	4.70	12.2	83.7
50	1.75	2.02	2.89	7.39	52.3
30	0.790	0.901	1.29	3.38	22.0
10	0.220	0.261	0.28	0.892	7.22

Results

Solvolysis

The solvolysis rate constants, k_s/s^{-1}, of Y-phenyl chloroformates in MeOH–MeCN mixtures at 25.0 °C are summarized in Table 1. Rates are faster for compounds with stronger electron-withdrawing substituents (Y), suggesting that the reaction is of an associative type with negative charge development at the carbonyl carbon in the transition state (TS). The Hammett plots, Fig. 1, show a sharp break in the curve at $\sigma_Y \cong 0$ to a large dependence of log k_s on the electron-withdrawing Y substituent ($\sigma_Y > 0$) on the phenoxide group suggesting changes in the TS structure; ρ_Y changes from *ca.* $\rho_Y \cong 0.8$ for $\sigma_Y < 0$ to $\rho_Y \geqslant 1.6$ for $\sigma_Y > 0$.

The activation parameters, $\Delta H^{\ddagger}$ and $\Delta S^{\ddagger}$, calculated from the k_s values at three temperatures (Table 1) for phenyl chloroformate (Y = H) in MeOH–MeCN mixtures are shown in Table 2. Relatively low $\Delta H^{\ddagger}$ (8–10 kcal/mol^{-1}) and large negative $\Delta S^{\ddagger}$ values (-34 to -47 e.u) are within the ranges of those for a typical S_N2 reaction.

The solvent deuterium isotope effects in Table 3 are relatively large, $k_{MeOH}/k_{MeOD} = 2.3 \pm 0.2$, indicating that the reactions are predominantly general-base catalysed.[3c] A small increase in the k_{MeOH}/k_{MeOD} value to 2.5 for Y = *p*-NO_2 may again suggest a change in the TS structure to a highly associative type with the strong general-base catalysis. However, the difference is certainly too small to warrant definitive interpretation.

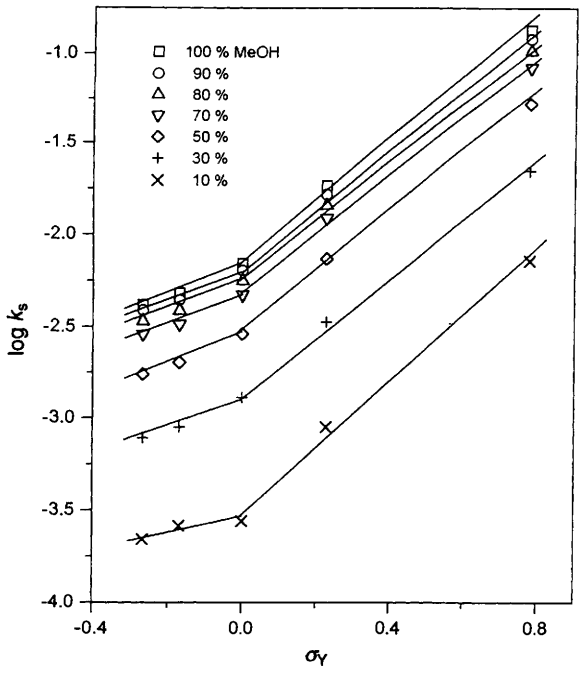


Fig. 1 Plots of log k_s *vs.* σ_Y for the solvolyses of Y-phenyl chloroformates in MeOH–MeCN mixtures at 25.0 °C

Table 2 Activation parameters for the solvolyses of phenyl chloroformate in MeOH–MeCN mixtures at 25.0 °C

MeOH (v%)	T/°C	$k_s/10^3$ s^{-1}	$\Delta H^{\ddagger}$/ kcal mol^{-1} [a]	$-\Delta S^{\ddagger}$/ cal mol^{-1} deg^{-1} [a,b]
100	15.0	3.40	9.9	34
	25.0	6.94		
	35.0	13.7		
90	15.0	3.22	9.5	35
	25.0	6.38		
	35.0	12.3		
80	15.0	3.80	10.0	34
	25.0	5.63		
	35.0	11.2		
70	15.0	3.04	10.0	35
	25.0	4.70		
	35.0	9.31		
50	15.0	1.47	9.1	39
	25.0	2.89		
	35.0	5.40		
30	15.0	0.673	8.5	42
	25.0	1.29		
	35.0	2.33		
10	15.0	0.152	8.0	47
	25.0	0.280		
	35.0	0.480		

[a] 1 cal = 4.184 J. [b] 1 cal mol^{-1} deg^{-1} ≡ 1 e.u.

Table 3 Solvent deuterium isotope effects, k_{MeOH}/k_{MeOD}, for the solvolyses of Y-phenyl chloroformates in 100% MeOH and MeOD at 25.0 °C

Y	$k_{MeOH}/10^3$ s^{-1}	$k_{MeOD}/10^3$ s^{-1}	k_{MeOH}/k_{MeOD}
p-OMe	4.14 ± 0.03[a]	1.73 ± 0.03[a]	2.3_9 ± 0.05[b]
p-Me	4.87 ± 0.06	2.04 ± 0.03	2.3_5 ± 0.05
H	6.94 ± 0.07	2.95 ± 0.04	2.3_5 ± 0.04
p-Cl	18.3 ± 0.4	8.13 ± 0.23	2.2_5 ± 0.08
p-NO_2	134 ± 3	53.4 ± 0.7	2.5_1 ± 0.07

[a] Standard deviation. [b] Standard error.

Aminolysis

The aminolysis rates are found to follow good second-order kinetics, eqn. (2), with negligible k_s values in acetonitrile. The

$$k_{obs} = k_s + k_2[AN] \quad (2)$$

second-order rate constants, k_2/dm^3 mol^{-1} s^{-1} in Table 4, were determined from the k_{obs} values of at least four aniline concentrations, [AN], under pseudo-first order condition, [AN] = 0.005–0.07 mol dm^{-3}, for [phenyl chloroformate] ≅ 1×10^{-4} mol dm^{-3}. No third-order or higher-order terms were detected, and also no complications were found in the determination of k_{obs} and in the linear plots of eqn. (2); this suggests that there is no base-catalysis or noticeable side reactions and the overall reaction follows the route giving in reaction (1). The ρ_X (ρ_{nuc}), β_X (β_{nuc}) and ρ_Y values are also shown in Table 4. In the determination of ρ_X, the σ_X^- constant for *p*-NO_2 is used. This is due to direct conjugation between the reaction site and the *p*-NO_2 group of aniline in a tight bond formation.

The activation parameters, $\Delta H^{\ddagger}$ and $\Delta S^{\ddagger}$, (Table 5), were determined for Y = H based on the k_2 values at three temperatures, 15.0, 25.0 and 35.0 °C. The $\Delta H^{\ddagger}$ and $\Delta S^{\ddagger}$ values are somewhat lower than those for the solvolysis given in Table 2.

The kinetic secondary α-deuterium isotope effects, k_H/k_D, involving deuteriated aniline nucleophiles are summarized in Table 6. The effects are all inverse type, $k_H/k_D < 1.0$, corresponding to an increase in the vibrational frequencies of the two N–H bonds (or one of the two can partially deprotonate as for the *p*-NO_2-aniline case) accompanied by steric hindrance to the nucleophilic attack.[11]

Discussion

Solvolysis

Chloroformate esters, **1**, are known to hydrolyse much more

1 **2**

slowly than other acid chlorides, RCOCl, an effect which is attributed to initial-state stabilization by π-electron resonance, **2**.[12] This resonance effect should be enhanced by increased electron donation from R, and opposed by the inductive electron withdrawing effect of the OR group. Comparison of the methanolysis rate constant, k_s/s^{-1}, at 25.0 °C, for phenyl chloroformate (6.94×10^{-3} s^{-1}) with those of benzoyl (4.33×10^{-3} s^{-1})[13] and cinnamoyl (63.7×10^{-3} s^{-1})[9] chloride indicates that the initial state stabilization by resonance electron donation is much greater for the phenoxy group ($\sigma_R = -0.32$, $\sigma_I = 0.39$)[14] than for the cinnamoyl group ($\sigma_R = \pm 0.15$, $\sigma_I = 0.07$) as expected from the large resonance substituent constant (σ_R) for the former. The much faster rate for cinnamoyl chloride may be ascribed to the low resonance electron donation of the cinnamoyl group leading to a low stabilization of the initial state. The opposing inductive effect (σ_I) appears to have little influence on the rate. Direct conjugation of the phenyl group ($\sigma_R = -0.08$, $\sigma_I = 0.11$) seems to be as strong as the resonance electron donation of the phenoxy group although σ_R has a small negative value. Since ρ_Y is positive (Fig. 1), resonance electron donation of the OR group ($\sigma_R < 0$) should destabilize the TS and inductive electron withdrawal ($\sigma_I > 0$) stabilizes the TS. Thus, the initial-state stabilization of large negative σ_R is the main influence on the rate, since the opposing σ_R and σ_I effects nearly cancel out in the TS.

Table 4 Rate constants, k_2 dm^3 mol^{-1} s^{-1}, for the reactions of Y-phenyl chloroformates with X-anilines in MeCN at 25.0 °C

	k_2/dm^3 mol^{-1} s^{-1}					
	Y					
X	*p*-OMe	*p*-Me	H	*p*-Cl	*p*-NO_2	ρ_Y[a]
H	3.67	4.59	6.37	13.0	73.2	1.26
p-Cl	1.13	1.28	1.82	3.87	17.1	1.16
m-Cl	0.447	0.554	0.896	1.39	7.94	1.19
m-NO_2	0.0847	0.113	0.158	0.303	1.27	1.22
p-NO_2	0.00473	0.00589	0.00945	0.0194	0.0811	1.20
ρ_X[b]	−2.27	−2.25	−2.22	−2.21	−2.30	
β_X[c]	0.79	0.79	0.77	0.77	0.80	

[a] Correlation coefficients ⩾ 0.997. [b] Correlation coefficients ⩾ 0.998. [c] Correlation coefficients ⩾ 0.998.

Table 5 Activation parameters for the reactions of phenyl chloroformate with X-anilines in MeCN at 25.0 °C

X	*T*/°C	k_2/ dm^3 mol^{-1} s^{-1}	$\Delta H^{\ddagger}$/ kcal mol^{-1}	$-\Delta S^{\ddagger}$/ cal mol^{-1} deg^{-1}[a]
H	15.0	4.25	5.2	37
	25.0	6.37		
	35.0	9.34		
p-Cl	15.0	1.16	5.7	34
	25.0	1.82		
	35.0	2.76		
m-Cl	15.0	0.550	5.7	39
	25.0	0.896		
	35.0	1.45		
m-NO_2	15.0	0.0931	7.8	35
	25.0	0.158		
	35.0	0.263		

[a] 1 cal mol^{-1} deg^{-1} ≡ 1 e.u.

The similarity of the effects of the phenyl and phenoxy groups on the solvolysis rates is extended to similar Hammett ρ_Y values (the slope of the plots of log k_s *vs.* σ_Y); the ρ_Y values are positive for both compounds with +1.2[13] and +0.8 to +1.6 for the phenyl and phenoxy derivatives, respectively. This provides evidence for an associative TS in a rate limiting attack with little bond cleavage for the methanolysis of phenyl chloroformates. In contrast, the solvolytic behaviour of cinnamoyl chlorides is quite different with a negative ρ_Y value (ρ_Y = −1.5),[9] for which a dissociative TS in a concerted process has been proposed. The break at $\rho_Y \cong 0$ in the plots of log k_s *versus* σ_Y (Fig. 1) suggests that the TS structure changes to a more associative type for the electron withdrawing substituents with much tighter bond formation. In such cases, the Hammett plots may be viewed as curves not two distinct intersecting lines as shown.

The relatively small positive $\Delta H^{\ddagger}$ (8–10 kcal mol^{-1}) and large negative $\Delta S^{\ddagger}$ (−34 to −47 e.u.) values in Table 2 are characteristic of a reaction involving partial development of charge with a low degree of bond cleavage in the TS.[15] The values are in the range normally observed for associative S_N2 reactions. Thus, a large increase in the rate of solvolysis with electron-withdrawing substituents with large positive ρ_Y values and the relatively low activation parameters support an associative TS that involves bimolecular attack of methanol on the carbonyl carbon of the phenyl chloroformates. This mechanism is also consistent with general-base catalysis by MeOH with attack of MeOH on the carbonyl carbon as evidenced by the relatively strong solvent deuterium isotope effects observed,[3c,16] $k_{MeOH}/k_{MeOD} \cong 2.3$–2.5 (Table 3). The solvent deuterium isotope effects for the methanolysis of benzoyl chlorides are slightly smaller ($k_{MeOH}/k_{MeOD} \cong 1.2$–1.6) for the electron-donating substituents but are similar for the electron-withdrawing substituents ($k_{MeOH}/k_{MeOD} \cong 1.7$–2.3).[13]

We conclude that the methanolysis of phenyl chloroformates proceeds through a predominantly associative TS with rate-limiting attack of the nucleophile, MeOH, and a relatively low degree of bond cleavage.

Aminolysis

The second-order rate constants, k_2(dm^3 mol^{-1} s^{-1}), for the reactions of phenyl chloroformates with anilines are summarized in Table 4. The rate is faster for a stronger electron-withdrawing Y substituent ($\Delta\sigma_Y > 0$), which is similar to the trend found for the methanolysis reaction. The ρ_Y values are relatively large and positive, especially when fall-off[17] due to an intervening oxygen atom between the phenyl group and carbonyl carbon is accounted for. This provides evidence for an associative TS that involves bimolecular attack of the aniline nucleophile on the carbonyl carbon. Comparison of the aminolysis rate constant in acetonitrile at 25.0 °C indicates that phenyl chloroformate is the least reactive with aniline among the three compounds in the order, benzoyl chloride (14.0 dm^3 mol^{-1} s^{-1})[18] > cinnamoyl chloride (13.3 dm^3 mol^{-1} s^{-1})[9] > phenyl chloroformate (6.37 dm^3 mol^{-1} s^{-1}). This is again due to the stabilizing effect in the initial state of the strong resonance electron donating phenoxy group. The ρ_X (ρ_{nuc}) values in MeCN at 25.0 °C (ρ_X = −2.2 to −2.3) are similar to the corresponding values for the reactions of benzoyl chlorides (ρ_X = −2.1 to −2.8),[18] suggesting that both react with anilines by an associative S_N2 mechanism. Somewhat higher ρ_Y ($\rho_Y \cong$ +3.0 after correcting for the fall-off) values are also suggestive of a tighter TS for phenyl chloroformates than for benzoyl chlorides (ρ_Y = +1.2–2.2).[18] The observed values of β_X (β_{nuc}) ≅ 0.8 agree with the values of β_X = 0.70–0.85[6,19] for the reactions of benzoyl chlorides and fluorides with anilines, for which a concerted S_N2 mechanism with a tight TS has been proposed.

It is interesting to note that the values of ρ_X (ρ_X = −1.7–−2.5) and ρ_Y (ρ_Y = 1.3–4.0 after correcting for the fall-off due to an intervening vinyl group) for the reactions of cinnamoyl chlorides with anilines[9] in MeCN at 25.0 °C are also similar to the corresponding values for the reactions of benzoyl chlorides and phenyl chloroformates. However, there are notable differences. (*i*) The secondary kinetic isotope effects involving deuteriated aniline nucleophiles are normal for cinnamoyl chlorides, $k_H/k_D > 1.0$,[9] whereas they are inverse for benzoyl chlorides and phenyl chloroformates, $k_H/k_D < 1.0$.[13] (*ii*) For the reactions of benzoyl chlorides (also fluorides) and phenyl chloroformates cross-interaction constants ρ_{XY},[17] defined by eqns. (3*a*) and (3*b*), are negative (ρ_{XY} = −0.85[13] and −0.04 respectively, whereas for the reactions of cinnamoyl chlorides

Table 6 Kinetic isotope effects for the reactions of Y-phenyl chloroformates with deuteriated X-anilines in MeCN at 25.0 °C

X	Y	k_H/dm^3 mol^{-1} s^{-1}	k_D/dm^3 mol^{-1} s^{-1}	k_H/k_D
p-Cl	*p*-OMe	1.13 ± 0.01[a]	1.33 ± 0.01[a]	0.850 ± 0.009[b]
	p-Me	1.28 ± 0.01	1.56 ± 0.01	0.821 ± 0.008
	H	1.82 ± 0.01	2.31 ± 0.02	0.780 ± 0.008
	p-Cl	3.87 ± 0.02	5.11 ± 0.03	0.757 ± 0.006
	p-NO_2	17.1 ± 0.1	22.5 ± 0.1	0.760 ± 0.005
ρ_Y		1.16	1.21	
m-NO_2	*p*-OMe	0.0847 ± 0.0001	0.101 ± 0.001	0.836 ± 0.008
	p-Me	0.113 ± 0.001	0.131 ± 0.001	0.863 ± 0.009
	H	0.158 ± 0.001	0.168 ± 0.001	0.940 ± 0.008
	p-Cl	0.303 ± 0.002	0.410 ± 0.003	0.739 ± 0.007
	p-NO_2	1.27 ± 0.01	1.62 ± 0.01	0.784 ± 0.008
ρ_Y		1.22	1.17	

[a] Standard deviation. [b] Standard error.

$$\log (k_{XY}/k_{HH}) = \rho_X\sigma_X + \rho_Y\sigma_Y + \rho_{XY}\sigma_X\sigma_Y \quad (3a)$$

$$\rho_{XY} = \frac{\partial\rho_Y}{\partial\sigma_X} = \frac{\partial\rho_Y}{\partial\sigma_Y} \quad (3b)$$

ρ_{XY} is positive ($\rho_{XY} = +0.88$).[9] It has been predicted that the sign of ρ_{XY} is negative for a concerted (S_N2) mechanism while it is positive for a stepwise mechanism with rate-limiting[20] breakdown of a tetrahedral intermediate. Thus, the negative value of ρ_{XY} for the phenyl chloroformate reactions is again consistent with the proposed concerted mechanism.

The low values of the activation parameters, $\Delta H^{\ddagger}$ (5–8 kcal mol^{-1}) and $\Delta S^{\ddagger}$ (−34 to −38 e.u.), in Table 5 are in line with an associative TS with relatively little bond breaking; a low $\Delta H^{\ddagger}$ value is indicative of a low degree of bond cleavage.[15] For the reactions involving a pre-equilibrium of tetrahedral intermediate formation, negative $\Delta H^{\ddagger}$ values are often obtained.[8] Our finding of low but positive $\Delta H^{\ddagger}$ values is an indication that no such stepwise mechanism is likely for the reactions of phenyl chloroformates. The proposed associative S_N2 mechanism is further supported by the inverse secondary kinetic isotope effects ($k_H/k_D = 0.74$–0.94) involving deuteriated aniline nucleophiles in Table 6. A tight bond formation of the aniline nucleophile should increase the N–H vibrational frequencies of the aniline substantially due to severe steric inhibition in the TS. The smaller values of k_H/k_D for the reactions of the compounds with electron-withdrawing Y substituents are consistent with the tighter bond making expected for the electron-withdrawing Y substituents.[11] This is evidence for a mechanism in which rate-limiting attack is involved. For the acyl transfer reactions that are believed to proceed by rate-limiting breakdown of a tetrahedral intermediate the corresponding k_H/k_D values are found to be greater than unity ($k_H/k_D > 1.0$).[21]

The reaction occurs through a concerted mechanism since the tetrahedral intermediate, $T^{\pm}$, is too unstable to exist. The decomposition of the adduct, **3**, is likely to be facile because of resonance electron donation from the phenoxy group.† It has been shown theoretically[22] as well as experimentally that strong resonance electron donating groups like MeO, EtO and PhO provide a strong push in the adduct, **3**,[10] to expel both the amine and the leaving group, Cl^-. Our theoretical analysis has indicated that an electron donating group (Y) actually lowers both TSs surrounding the intermediate, which results in the destabilization of the intermediate, $T^{\pm}$.[22] The depression was

† A referee suggested, and we agree, that since the evidence presented for the rate-limiting attack in a concerted process is not very convincing the possibility of a two-step mechanism cannot be entirely precluded.

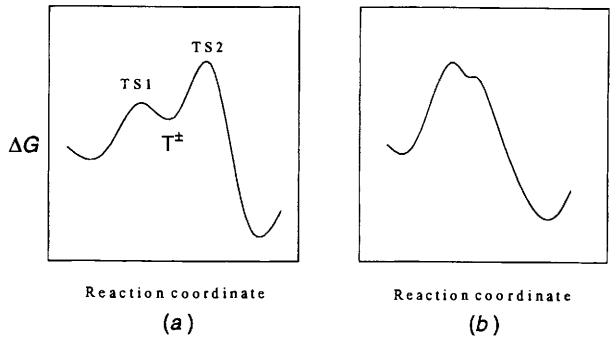
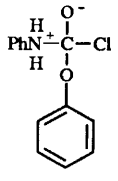


Fig. 2 Schematic diagram for the effect of a strong electron-donating substituent (Y) on the stability of intermediate, $T^{\pm}$; (*a*) ⟶ (*b*)



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actually greater for the higher barrier, TS2 in Fig. 2, in agreement with the experimental results.[23] The resulting destabilization of the adduct may become so strong that the intermediate, $T^{\pm}$, cannot exist and becomes a TS, (Fig. 2). Strong electron donation from the phenoxy group that destabilizes $T^{\pm}$ may account for a change from stepwise for the cinnamoyl chlorides to a concerted mechanism for the phenyl chloroformates.

Conclusions

The experimental results suggest that the methanolysis and aminolysis of phenyl chloroformates proceed by an associative S_N2 type mechanism. The proposed mechanism for the reactions of phenyl chloroformates is similar to that for substitution on benzyl and benzoyl chlorides. The TS structure resembles a trigonal bipyramid or a tetrahedral addition compound. In these structures a large amount of electron transfer from, and bond formation with, the nucleophile are possible in the associative TS. Electron-donating groups on benzyl and benzoyl chlorides, therefore, oppose charge transfer from the nucleophile so that the TSs are destabilized with a rate decrease. This is in contrast to the lowering of both TS1 and TS2 by the electron-donating substituents shown in Fig. 2. In

these TSs, expulsion of amine nucleophile (TS1) and leaving group (TS2) is involved from the tetrahedral intermediate, $T^{\pm}$, so that both TSs are stabilized and depressed by the electron-donating substituents leading to an insignificant lifetime of $T^{\pm}$. When the tetrahedral species $T^{\pm}$ becomes too unstable to exist because of the presence of a strong electron-donor the reaction can occur through a concerted mechanism, as we found for the reactions of phenyl chloroformates.

Experimental

Materials

Merck GR acetonitrile was used after three distillations. Merck analytical grade methanol was used without further purification. The aniline nucleophiles used were Aldrich GR, which were redistilled or recrystallized before use.[18] Preparation of deuteriated anilines was as described previously.[13,18] The analysis (NMR spectroscopy) of the deuteriated nucleophiles showed more than 99% deuterium content, so that no corrections to kinetic isotope effects for incomplete deuteriation were made. Aldrich Y-phenyl chloroformates were used after identification by GC–MS and TLC analysis without further purification. Since they are corrosive and moisture sensitive they were treated in a glove box filled with N_2 gas.

Kinetic procedures

Rates were measured conductimetrically at 25.0 + 0.05 °C. The conductivity bridge used in this work was a self-made computer automatic A/D converter conductivity bridge. Pseudo-first-order rate constants, k_{obs}, were determined by the Guggenheim method[24] with a large excess of aniline; [phenyl chloroformate] $\cong 1 \times 10^{-4}$ mol dm^{-3} and [aniline] = 0.005–0.07 mol dm^{-3}. Second-order rate constants, k_2, were obtained from the slope of a plot of k_{obs} *vs.* [AN] with more than four concentrations of aniline, eqn. (2). The k_2 values in Table 4 are the averages of more than three runs and were reproducible to within ±3%.

Product analysis

Aminolyses [$YC_6H_4OC(=O)NHC_6H_4X$]. *p*-Methoxyphenyl chloroformate was treated with an excess of aniline with stirring for more than 15 half-lives at 25.0 °C in acetonitrile. The ammonium salt was separated by filtration and the solvent was evaporated under reduced pressure. The isolated products were purified by recrystallization from hexane and identified by TLC, mp, NMR, IR and GC–MS. The same method was used for all the other products.

Solvolyses [$YC_6H_4OC(=O)OMe$]. *p*-Methoxyphenyl chloroformate was treated with an excess of methanol with stirring for more than 15 half-lives at 25.0 °C, and the products were isolated by evaporating the methanol under reduced pressure. The HCl gas was removed by high vacuum evaporation and the products were identified by TLC, mp NMR, IR and GC–MS. The same method was used for all the other products. The product analysis data are given below.

***p*-Methoxyphenyl anilinoformate.** R_f (20% ethyl acetate–hexane) 0.34; mp 124–125 °C; $\delta_H(CDCl_3$–[$^2H_6$]DMSO) 6.7–7.5 (Ph-H, 9 H, m), 9.5 (N H, 1 H, br), 3.75 (OCH_3, 3 H, s); ν_{max}(Nujol)/cm^{-1} 3400 (N–H), 1700 (C=O); *m*/*z* 243 (M^+).

***p*-Tolyl anilinoformate.** R_f (20% ethyl acetate–hexane) 0.50; mp 132–134 °C (lit.,[25] 135–137 °C); $\delta_H(CDCl_3$–[$^2H_6$]DMSO) 6.7–7.6 (Ph–H, 9 H, m), 9.6 (NH, 1 H, br), 2.3 (CH_3, 3 H, s); ν_{max}(Nujol)/cm^{-1} 3350 (N–H), 1700 (C=O); *m*/*z* 227 (M^+).

Phenyl anilinoformate. R_f (20% ethyl acetate–hexane) 0.45; mp 107–109 °C (lit.,[25] 108–110 °C); $\delta_H(CDCl_3$–[$^2H_6$]DMSO) 7.0–7.7 (Ph–H, 10 H, m), 9.5 (NH, 1 H, br); ν_{max}(Nujol)/cm^{-1} 3330 (N–H), 1710 (C=O); *m*/*z* 213 (M^+).

***p*-Chlorophenyl anilinoformate.** R_f (20% ethyl acetate–hexane) 0.45; mp 146–148 °C (lit.,[25] 148–150 °C); $\delta_H(CDCl_3$–[$^2H_6$]-DMSO) 6.8–7.6 (Ph-H, 9 H, m), 9.4 (NH, 1 H, br); ν_{max}-(Nujol)/cm^{-1} 3350 (N–H), 1710 (C=O); *m*/*z* 247 (M^+).

***p*-Nitrophenyl *m*-Chloroanilinoformate.** R_f (20% ethyl acetate–hexane) 0.26; mp 116–117 °C; $\delta_H(CDCl_3$–[$^2H_6$]DMSO) 6.9–7.8 (Ph-H, 8 H, m), 9.7 (N H, 1 H, br); ν_{max}(Nujol)/cm^{-1} 3400 (N–H), 1700 (C=O); *m*/*z* 292 (M^+).

***p*-Methoxyphenyl methoxyformate.** R_f (20% ethyl acetate–hexane) 0.43; $\delta_H(CDCl_3)$ 6.6–7.2 (Ph-H, 4 H, m), 3.8 [C(=O)OCH_3, 3 H, s], 3.6 (*p*-OCH_3-Ph, 3 H, s); ν_{max}(neat)/cm^{-1} 2900 (C–H aromatic), 1750 (C=O), 1230 (C–O–C); *m*/*z* 182 (M^+).

***p*-Tolyl methoxyformate.** R_f (20% ethyl acetate–hexane) 0.47; $\delta_H(CDCl_3)$ 6.6–7.3 (Ph-H, 4 H, m), 3.8 (OCH_3, 3 H, s), 2.3 (*p*-CH_3, 3 H, s); ν_{max}(neat)/cm^{-1} 3000 (C–H aromatic), 1760 (C=O), 1250 (C–O–C); *m*/*z* 166 (M^+).

Phenyl methoxyformate. R_f (20% ethyl acetate–hexane) 0.44; $\delta_H(CDCl_3)$ 6.8–7.2 (Ph-H, 5 H, m), 3.8 (OCH_3, 3 H, s); ν_{max}(neat)/cm^{-1} 2950 (C–H aromatic), 1750 (C=O), 1230 (C–O–C); *m*/*z* 152 (M^+).

***p*-Chlorophenyl methoxyformate.** (20% ethyl acetate–hexane) 0.41; $\delta_H(CDCl_3)$ 6.7–7.4 (Ph-H, 4 H, m), 3.9 (OCH_3, 3 H, s); ν_{max}(neat)/cm^{-1} 3000 (C–H aromatic), 1760 (C=O), 1250 (C–O–C); *m*/*z* 186 (M^+).

***p*-Nitrophenyl methoxyformate.** R_f (20% ethyl acetate–hexane) 0.35; mp 104–105 °C; $\delta_H(CDCl_3)$, 7.3–8.2 (Ph-H, 4 H, m), 3.9 (OCH_3, 3 H, s); ν_{max}(Nujol)/cm^{-1} 1760 (C=O), 1300 (C–O–C); *m*/*z* 197 (M^+).

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