Studies of the Borderline between Concerted and Stepwise Mechanisms of Elimination: *E*1cB Elimination of Fluoren-9-ylmethyl Carboxylate Esters

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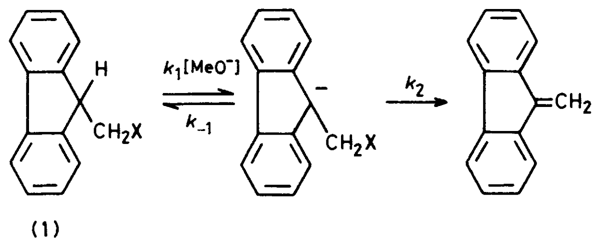
Rates of β-elimination of carboxylate leaving groups from fluoren-9-ylmethyl carboxylate esters in methanolic sodium methoxide at 25° are reported. An *E*1cB mechanism with rate-determining formation of a carbanion intermediate is assigned on the basis of near identity of measured elimination rates and rates of carbanion formation predicted from a Taft correlation, and the similarity with elimination of 1-(1-acetoxy-1-methylethyl)indene for which the mechanism has been established by Ahlberg and Thibblin. Values of $\rho = 0.42$ and $\beta_{lg} = 0.27$ measured for substituted benzoate leaving groups are a little larger than expected (*ca.* 0.24 and 0.18, respectively) and the discrepancy is tentatively ascribed to conformational enhancement of remote substituent effects, rather than to a contribution of *E*2 elimination. The effects of alkyl and aryl substitution α to the leaving group are discussed, especially in relation to the borderline between concerted and stepwise mechanisms. The measurements fail to confirm an earlier inference that the borderline shows a discontinuity in transition-state structure at the point of mechanistic change.

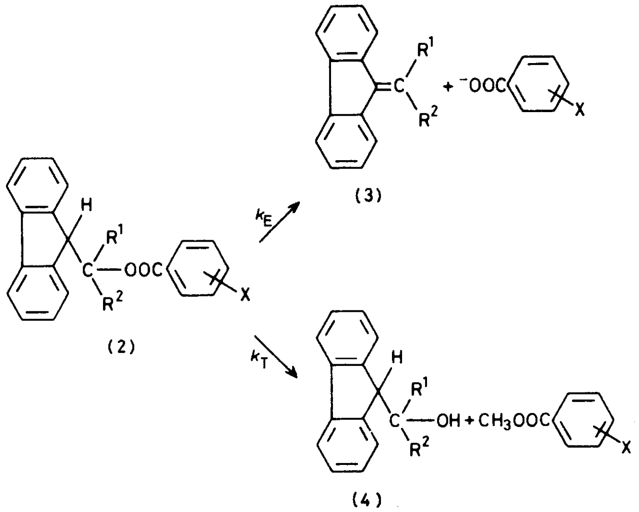
For the leaving groups OH or OMe β-eliminations of fluorene derivatives (1) to form dibenzofulvene in aqueous sodium hydroxide or methanolic sodium methoxide occur by an *E*lcB mechanism (Scheme 1).[1,2] In this paper we describe an investigation of the mechanism of the corresponding reaction of carboxylate groups. Compared with other leaving groups eliminations of carboxylate ions have been little studied, because the reaction normally observed is ester exchange or hydrolysis. In the presence of strongly activating β-substituents such as RCO,[3-5] $PhSO_2$,[6] indene,[7] or fluorene,[8] however, the elimination reaction can compete. For fluorenylmethyl esters the two reactions are of comparable rate and a combined analysis of kinetics and products yields rate constants for both processes.

For the OH and OMe leaving groups reprotonation of the carbanion intermediate only just exceeds the rate of leaving-group expulsion.[1,2] It follows that for the more reactive carboxylate leaving groups the form of *E*lcB mechanism likely to occur is that in which the carbanion is formed irreversibly. A well known difficulty with this mechanism is that it is not easily distinguished from a concerted *E*2 mechanism. The procedure for making this distinction has, however, been established by Fedor.[3,4] An *E*2 mechanism is indicated if the rate of elimination and the sensitivity of the rate to a change in leaving group are greater than expected of rate-determining carbanion formation. An *E*lcB mechanism is implied when this is not the case. Ideally an *E*lcB mechanism is confirmed by observation of a change in rate-determining step to reversible carbanion formation, as signalled by kinetic saturation in a suitable buffer[4] or by measurements of isotope effects for competing exchange and elimination reactions.[1,9]

In so far as the present paper forms part of a continuing investigation[10,11] of the borderline between concerted and stepwise mechanisms of elimination a principal point of interest is that since better leaving groups such as I, Br, and Cl give evidence of reaction by an *E*2 mechanism,[10,11] eliminations of carboxylate groups may fall close to the *E*2–*E*1cB borderline. In this respect a useful probe of mechanism is provided by benzoate leaving groups, for which the Hammet ρ may be expected to offer a sensitive indication of the presence and extent of leaving-group bond-breaking in the transition state. Moreover, although not observed in practice, the possibility can be considered that a change in mechanism accompanying variation of substituents in the benzoate ring will be reflected in a break in the Hammett plot.



Scheme 1



Scheme 2

Results

Rate constants for elimination of acetate, pivalate, carbonate, carbamate, carbanilate, and substituted benzoate leaving groups have been measured at 25° in methanolic sodium methoxide from the increase in absorption of the dibenzofulvene product (3). Normally, elimination is accompanied by transesterification forming fluoren-9-ylmethanol as shown in Scheme 2. Measured second-order rate constants (k_2) thus represent the sum of contributions from elimination and

Table 1. Rate constants for elimination and transesterification of substituted fluoren-9-ylalkyl benzoates [$BiphCHCH(R)OOCC_6H_4X$] [a] in NaOMe–MeOH at 25° [b]

X	R = H 10^3k_E	 10^3k_T	R = Bu^t 10^3k_E	 10^3k_T	R = Biph [a] 10^3k_E	 10^3k_T
p-NO_2	97.4	626	14.0	3.0	2.09	27.0
m-NO_2	81.1	635				
m-Cl	54.5	114	9.01			
p-Cl	61.4	60.2			1.00	0.824
H	35.8	14.9	5.53		0.608	0.112
m-Me	39.2	11.5			0.685	0.114
p-MeO	35.3	6.2	3.88			
p-Me_2N	18.7					
m-O^-	8.8					

[a] Biph denotes the biphenylyl group, *i.e.* 9-benzoyloxy-9,9′-bifluorenyls: there is no H α to the leaving group for these substrates. [b] Units of l mol^{-1} s^{-1}.

Table 2. Rate constants and fractions of elimination (f_E) and transesterification for fluoren-9-ylalkyl acetates and benzoates [$BiphCHC(R^1R^2)OOR$] [a] in NaOMe–MeOH at 25°

R^1,R^2	10^3k_E OAc	 OBz	10^3k_T OAc	 OBz	f_E OAc	 OBz
H,H	42.5	35.8	77.0	14.9	0.36	0.71
H,Me	5.82	4.22	5.82	2.06	0.50	0.67
H,Pr^i		4.11		0.350		
H,Bu^t		5.53				
H,Ph	5.20	5.62	27.1	2.06	0.16	0.73
Biph [a]	0.267 [b]	0.608	2.60 [b]	0.112	0.095	0.84
Me,Me	0.0384	0.0564	0.181	0.0299	0.175	0.65

[a] Biph denotes biphenylyl, *i.e.* 9-benzoyloxy- or 9-acetoxy-9,9′-bifluorenyls. [b] Ref. 11.

Table 3. Rate constants for ionisation or elimination of substituted 9-methylfluorenes ($BiphCHCH_2X$) in NaOMe–MeOH at 25°

X	Process [a]	σ_I	10^2k/l mol^{-1} s^{-1}
Me	I	−0.04	0.00853 [b]
H	I	0	0.0126 [b]
Ph	I	0.12	0.0374 [b]
NMe_2	I	0.06	0.640 [c]
OMe	I	0.29	0.814 [d]
$OOCNMe_2$	E		0.201
OH	I	0.22	0.246 [e]
OOCNHPh [f]	E		3.24
OAc [f,g]	E	0.40	4.25
OOCPh [f]	E	0.42	3.58
$OOCC(CH_3)_3$ [f]	E	0.39	1.49
$OOCOCH_3$ [f]	E		10.1

[a] I indicates ionisation, E elimination. [b] Calculated from measurements of tritium exchange at 45° extrapolated to 25° assuming $\Delta S^\ddagger = -1$ cal K^{-1} mol^{-1}, the value measured for fluorene, and $k_H/k_D = (k_H/k_T)^{1.442}$, A. Streitwieser, jun., A. P. Marchand, and A. H. Pudjaatmaka, *J. Am. Chem. Soc.*, 1967, **89**, 693. [c] Ref. 21. [d] Ref. 2. [e] Ref. 1*a*. [f] Corrected for accompanying ester exchange. The fractions of elimination are: OAc, 0.36; OBz, 0.71; $OOCCMe_3$, 0.69; OOCOMe, 0.72; OOCNHPh, 0.75. [g] *Cf.* rate constant of 5.3 × 10^{-2} measured by Ahlberg and Thibblin.

transesterification k_E and k_T. Individual rate constants were separated by measuring the optical density of the dibenzofulvene when reaction was complete and comparing it with that expected for 100% elimination, making corrections for absorbances of other species present. Rate constants k_E and k_T for substituted benzoates are shown in Table 1, and the effect of alkyl or aryl substitution α to the leaving group [R^1 and R^2 in (2)] is shown in Table 2. Table 1 also includes rate constants for fluoren-9-ylmethyl benzoates bearing an α-t-butyl group [(2; R^1 = Bu^t, R^2 = H)] and an α-fluorenyl group [*i.e.* 9-aroyloxy-9,9′-bifluorenyls (2; R^1, R^2 = biphenylyl)]. In general, relative rates of elimination and ester exchange do not vary dramatically, but the ester exchange reaction is more sensitive to electronic effects and the pattern of steric effects on the two reactions also differs.

Elimination rate constants and fractions of elimination for acetate, pivalate, methyl carbonate, dimethylcarbamate, carbanilate, and unsubstituted benzoate leaving groups are listed in Table 3 (*cf.* footnote *f*) together with rate constants for ionisation of 9-XCH_2-substituted fluorenes (X = H, Me, Ph, OH, OMe, NMe_2) collected from the literature. For X = H, Ph, and Me the reported ionisation rate constants at 25° are extrapolated from Streitweiser's tritium isotope exchange measurements at 45°,[12] assuming that entropies of activation are the same as that measured for fluorene,[13] and corrected for tritium isotope effects using k_H/k_T 15.4 corresponding, through the Swain–Schaad relationship [14] [$k_H/k_T = (k_H/k_D)^{1.442}$], to the average value of k_H/k_D = 6.7 observed for a number of fluorene derivatives.[2,13,14] Also shown in Table 3 are σ_I values for substituents and leaving groups, based on ionisation of substituted acetic acids.[15] For the carboxylate groups these were estimated from the ionisation constants of the acyloxyacetic acids and $\sigma_I = 4.712 - pK_a(XCH_2COOH)/3.95$; [15] or for pivalic acid from a plot of σ_I for acyloxyacetic acids [16] so derived against the pK_a of the corresponding carboxylic acids. In the case of fluoren-9-ylmethyl acetate the rate constant has also been measured by Thibblin,[8] as 0.053 l mol^{-1} s^{-1}, compared with 0.043 in Table 3.

The measurements for the methyl carbonate (X = $OOCOCH_3$), dimethylcarbamate (X = $OOCNMe_2$), and carbanilate derive from fluoren-9-ylmethyl chloroformate. In methanol in the absence of base the chloroformate undergoes a solvolysis reaction with rate constant 3.4×10^{-3} s^{-1} as measured by protonation of proton sponge using the technique of Luton and Whiting.[17] This is presumed due to loss of HCl and formation of the methylcarbamate, the reaction that occurs for methyl chloroformate with rate constant 1.6×10^{-4} s^{-1}; [18] the lower rate constant than for the fluorenyl derivative is consistent with the known acceleration of the reaction by electron-withdrawing substituents.[18] The rate constant for the methyl carbamate therefore comes from reaction of a stock solution of fully reacted chloroformate in methanol from which the methyl carbamate was not isolated. The dimethyl carbamate and carbanilate groups were prepared from the chloroformate following Carpino and Han.[19]

For fluoren-9-ylmethyl acetate, measurements were also made in aqueous trimethylamine buffers (containing 10% EtOH). The reaction shows general base catalysis with no indication of buffer saturation, even with [Me_3NH^+] 0.75M.[20]

A number of measurements of primary isotope effects were made. For elimination of fluoren-9-ylmethyl 3-chlorobenzoate k_H/k_D = 6.4, based on single measurements of olefin : alcohol product ratios for protio- and deuterio-compounds, and for the 4-methoxybenzoate k_H/k_D = 7.8 ± 1.3 from three measurements. For the corresponding transesterification of the two substrates k_H/k_D = 1.3 and 2.0 ± 0.25, respectively. For the αα-dimethyl benzoate k_H/k_D = 7.9 for elimination and 1.5 for ester exchange. The combination of kinetic and product measurements required for each isotope measurement gives values of lower precision than usual, especially the small values for ester exchange.

A solvent isotope effect k_{MeOD}/k_{MeOH} = 2.55 was measured for elimination of α-t-butylfluoren-9-ylmethyl benzoate (2; R^1 = Bu^t, R^2 = X = H) for which the transesterification reaction is negligible. The reaction in MeOD was inspected for signs of departure from first-order kinetics indicative of isotope exchange in competition with elimination, but nothing was found.

Measurements of ρ for elimination of fluoren-9-ylmethyl benzoates, for the corresponding substrates bearing a t-butyl group α to the leaving group, and for 9-benzoyloxy-9,9′-bifluorenyls based on the rate constants listed in Table 1 were 0.42 ± 0.04, 0.53 ± 0.02, and 0.72 ± 0.07, respectively. In addition an approximate ρ of 0.18 ± 0.04 was obtained for elimination of *p*-methoxy, H, *m*-nitro, and *p*-nitro-substituted fluoren-9-ylmethyl benzoates promoted by trimethylamine base in aqueous buffers containing 10% ethanol with rate constants and fractions of elimination (in parentheses) of 1.54 (0.95), 2.00 (0.93), 2.47 (0.69), and 2.5 (0.55) $\times 10^{-3}$ l mol^{-1} s^{-1}, respectively. For reaction of fluoren-9-ylmethyl benzoates elimination rate constants are subject to some uncertainty, particularly for electron-withdrawing substituents, due to correction for the competing ester exchange reaction. The product analysis based on the absorbance of dibenzofulvene also required correction for the absorbance of benzoate anions and the ester reactant (see below). In this respect rate constants and values for the α-t-butyl and bifluorenyl benzoates had the advantage that ester exchange was unimportant in the former case while in the latter the bifluorenylidene product absorbed at sufficiently long wavelength ($\lambda_{max.}$ 455 nm) that correction for absorbances of other product or reactant species was unnecessary. For the fluorenylmethyl benzoate the point for the negatively charged *m*-O^- substituent deviates negatively from the Hammett line and was not included in the correlation. Save for this substituent, the substituent constants used were those of Okamoto and Brown.[15]

Discussion

Mechanism of Elimination.—As discussed above *E*2 and irreversible *E*lcB mechanisms of elimination may be distinguished by comparing observed rates of elimination with extrapolated rates of ionisation to form a β-carbanion using a suitable free-energy relationship for the latter reaction. Agreement between the two rates indicates an *E*lcB elimination, a greater observed elimination rate, an *E*2 mechanism.[4,10]

Figure 1 shows a plot of log *k versus* σ_I[16] for 9-XCH_2-substituted fluorenes in which previously measured ionisation rate constants [1,2,10,12,21] for X = H, Me, Ph, OH, OMe, and NMe_2 are shown as open circles. The ionisation rates were obtained from deuterium or tritium exchange measurements and are corrected for isotope effects: the values for H, Me, and Ph, were extrapolated from measurements by Streitwieser at a 20° higher temperature.[12] Rate constants for elimination of the carboxylate leaving groups acetate, benzoate, and pivalate are included in the plot as filled circles. With the exception of the dimethylamino-group it can be seen that all the points are correlated satisfactorily by a single straight line (slope = 5.85 ± 0.3).

The deviation of the point for dimethylamino has been discussed before.[2] It is consistent with Bordwell's finding that in equilibrium ionisations of 9-substituted fluorenes methyl substitution γ to the ionising hydrogen *increases* acidity, contrary to the expected inductive and solvation effects of a methyl substituent and in contrast to its effect at the β-position.[22] The behaviour is reasonably ascribed to release of non-bonding interactions in forming a trigonal carbanion from tetrahedral reactant and bears comparison with the *gem*-dialkyl effect in cyclisation reactions.[23] One may expect it to operate on rates as well as equilibria and to be reflected in a positive deviation from a free-energy plot based on inductive substituent constants. For this reason the points for NMe_2 and OMe were omitted from the correlation in Figure 1. The value of σ_I for NMe_2 is also poorly defined [16] and probably depends on the solvent.

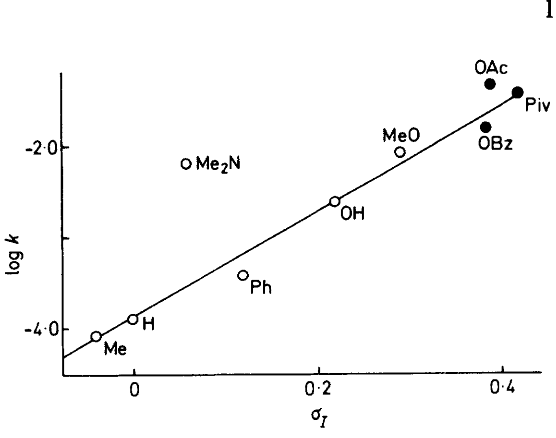


Figure 1. Plot of log *k versus* σ_I for isotope exchange (○) and elimination (●) of 9-XCH_2-substituted fluorenes in NaOMe–MeOH at 25°

Table 4. Carbanion formation for various activating groups at 25° [a]

X-CH_3	pK_a [b] DMSO	ρ*	10^3k/l mol^{-1} s^{-1} [c] NaOMe–MeOH or (NaOEt–EtOH)
$EtOOCCH_3$		1.78	0.164 [d]
NO_2CH_3	17.2	1.9	(14.4)
Indene [e]	20.1	2.1	0.39 [b]
Fluorene	22.6	2.25	0.085
$PhCOCH_3$	24.7	3.2	(19.5)
$NCCH_3$	31.3	3.8	(0.37)
$PhSO_2CH_3$	29.0	4.9	(3.1)

[a] Except as indicated. [b] W. E. Matthews, J. E. Bares, J. E. Bartmess, F. G. Bordwell, F. S. Cornforth, G. E. Drucker, Z. Margollin, R. J. McCollum, and N. R. Vanier, *J. Am. Chem. Soc.*, 1975, **97**, 7006. [c] For methyl-substituted compounds. [d] 35°. [e] ρ* and *k* for 1-(1-X-1-methylethyl)indene at 30°. [f] *k* calculated from Taft plot.

Use of σ_I in Figure 1 contrasts with earlier use of σ*.[10] The difference arises because substituent constants for carboxylate groups were obtained from the ionisation constants of substituted acetic acids and for consistency other σ_I values were defined in the same way. The value ρ_I = 5.85 converts into ρ* = 2.6 (0.45ρ_I) which compares with ρ* = 2.25 based on σ* and ionisation rates of the substituents H, Me, Ph, and OH only.[10] In terms of the earlier plot therefore carboxylate groups would show a small positive deviation from the correlation.

The magnitude of ρ_I or ρ* is important in identifying deviations from the correlation. Substantial deviations are seen for elimination of the strongly electronegative leaving groups iodide, bromide, chloride, phenylthiolate, phenylsulphonyl, and *p*-tolylsulphonate,[10] and for the halogens these have been interpreted in terms of an *E*2 mechanism of elimination.[10] Ahlberg and Thibbin [24] have pointed out that most of the measurements may be accommodated with a still acceptable fit to the data, by a substantially larger ρ* (*ca.* 3.6), but there is some independent evidence in favour of a small ρ*. Table 4 compares ρ* values for different carbanion-forming reactions,[24-27] and also pK_a values and rate constants for the parent and methyl-substituted substrates respectively. Stirling's measurements [6,25,26] in particular show that ρ* depends on the character of the carbanion stabilising substituent with values ranging from 1.7 to 4.9. The dependence on pK_a and

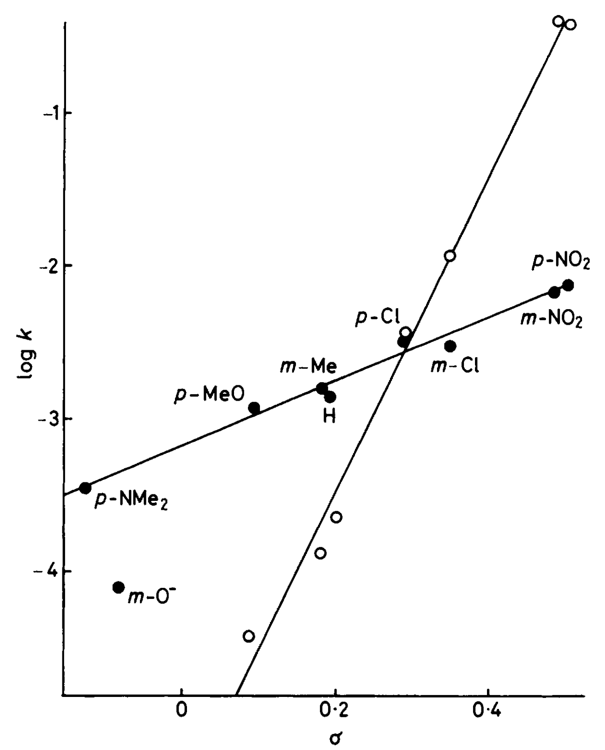


Figure 2. Plot of log k *versus* σ for elimination (●) and ester exchange (○) of substituted fluoren-9-ylmethyl benzoates in NaOMe–MeOH at 25°

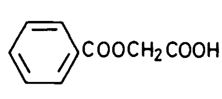
reactivity is not a simple one because of the influence of the intrinsic reactivity of the substrate [28] (probably reflecting the electron-delocalising ability of the substituent) and, possibly, internal return. However only $\rho^* = 1.78$ for CH_3COOEt [27] appears qualitatively out of line, and the low value of $\rho^* = 2.25$ for 9-methylfluorenes fits well with that for the structurally related 1-(1-methylethyl)indenes (2.1).[24]

Also consistent with a low ρ^* is the likelihood that the methoxy-substituent deviates positively from the Taft correlation, in accord with the effect detected by Bordwell.[22] Moreover, Streitwieser obtained a relatively slow tritium exchange rate for the strongly electron-withdrawing CF_3 substituent in 9-trifluoromethylfluorene.[12] Although CF_3 can yield slow ionisation rates by promoting internal return,[29] preliminary measurements by Koch suggest that this is not an important factor in the case of fluorene.[30]

With respect to the carboxylate leaving groups the conclusion to be drawn from Figure 1 is that the common correlation of ionisation and elimination rate constants favours carbanion formation in the rate-determining step of the elimination, *i.e.* an irreversible *E*1cB mechanism. It may also be noted that $(CH_3)_3CCOO$ is less reactive than CH_3COO, despite Bordwell's finding that $(CH_3)_3CSO_2$ increases the acidity of fluorene 150 times more than CH_3SO_2.[22] It appears that in contrast to γ-methyl substitution ε-methyl substitution causes little disturbance to a Taft plot.

To verify the mechanism of elimination a Hammett ρ was measured for substituted fluoren-9-ylmethyl benzoates. As with other carboxylate leaving groups elimination was accompanied by transesterification forming fluoren-9-ylmethanol (Scheme 2) and Hammett plots for both reactions are shown in Figure 2. The larger ρ of 2.07 applies to the transesterification and is comparable in magnitude with ρ values for other base-promoted ester exchange or hydrolysis reactions.[31]

For the elimination $\rho = 0.42 \pm 0.03$. This may be compared with $\rho = 0.16$ for the ionisation of substituted benzoyloxyacetic acids (5).[16] Formally the ratio of the two ρs should correspond with the ratio of ρ^* values for the ionisation of fluorenes and acid dissociation constants of substituted carboxylic acids ($\rho^* = 1.77$ [12]). It follows that the ρ to be expected for elimination may be computed as $0.16 \times 2.6/1.77 = 0.24$.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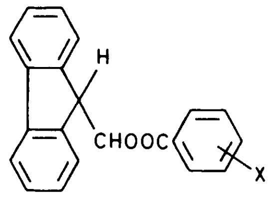
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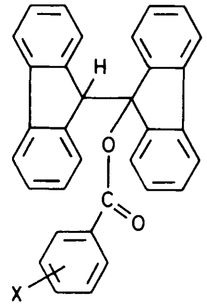
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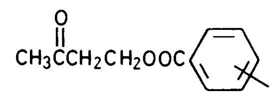
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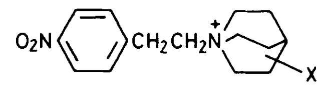
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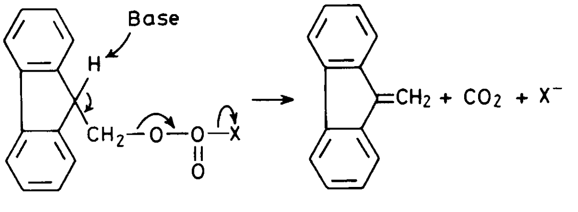
On this basis the measured ρ is about twice that expected of irreversible *E*1cB elimination. Arguably the discrepancy is within the uncertainty of the demonstrably unreliable method of calculation,[32] but the relatively large magnitude of the observed value is reinforced by measurements of $\rho = 0.53$ and 0.72, based on more limited ranges of substituents, for α-t-butylfluoren-9-ylmethyl benzoates (6) and 9-benzoyloxy-9,9′-bifluorenyls (7), respectively. The latter value especially is noteworthy, but the corresponding ρ for ester exchange is also large (3.0), and poor solvation of charge may be a significant factor for these bulky substrates.

A further comparison is with $\rho = 1.54$ for the ionisation of benzoic acids in methanol.[31] The kinetic ρ of 0.42 then gives $\beta_{lg} = -0.27$ as a measure of the effective charge felt by substituents in the transition state. The value may be compared with $\beta_{lg} = -0.18$ for elimination of substituted benzoates from benzoyloxybutan-2-ones (8) measured by Cavestri and Fedor.[3] Plotting rate constants for elimination of these substrates against pK_a values of the corresponding oxyacetic acids gave a common straight line with phenoxy leaving groups, for which an *E*1cB elimination had been definitely established by observation of kinetic saturation in amine buffers.[4] A $\beta_{lg} = -0.18$ was likewise found by Alunni and Jencks [33] in elimination of *p*-nitrophenethylquinuclidinium ions (9), for which a carbanion mechanism was also independently established.[9]

The comparison of ρ and ρ^* values and of β_{lg} values thus suggests that the sensitivity of the carboxylate eliminations to the nature of the leaving group is somewhat greater than expected of rate-determining formation of a carbanion.



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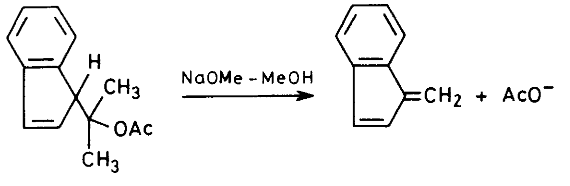

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Qualitatively, this is confirmed by measurements with the carbonate, carbanilate, and carbamate leaving groups. Relative values of σ_I are not available for these groups [15,34] but the observed fifty-fold variation in their elimination rates (Table 3), with an implied span of 0.7 in σ^*, appears remarkably large. The concerted fragmentation pathway of equation (1) might seem to offer an explanation of this but the absence of evidence of concertedness in simple eliminations of carboxylate groups and the closeness of the observed rates to expected rates of ionisation make it unlikely. Reversible carbanion formation is also excluded by lack of β-hydrogen isotope exchange accompanying elimination in MeOD.

On the other hand the measured ρ values fluctuate appreciably with reaction conditions. Thus Fedor and Cavestri [35] noted that the small ρ of 0.18 for benzoyloxybutan-2-ones increases to 0.37 in passing from aqueous medium to 45% w/w dioxan, and that a corresponding increase occurs for aryloxybutan-2-ones. This difference, if real, seems large for a simple medium effect. For fluoren-9-ylmethyl benzoates ρ is smaller in 90% aqueous ethanol (0.2) than in methanol (0.42). Here, however, the difference may be due to use of a neutral amine base (becoming positively charged in the transition state) rather than the negatively charged hydroxide ion for reasons of solubility.

For the benzoate leaving groups the most plausible explanation of the enhanced ρ and β_{lg} values would seem to be that they reflect some conformational flexibility in the molecules associated with large and non-rigid separation of substituent and reaction sites. For benzoyloxybenzoate anions ($\rho = 0.16$) one may speculate that the hydrophilic carboxylate and hydrophobic substituent groups repel each other, thereby minimising transmission of the substituent effect. For fluorenyl anions a hydrophobic attraction of fluorenyl and aryl rings seems more likely, rendering the substituent less remote and giving a larger ρ. Conceivably this explanation is not inconsistent with the medium sensitivity observed for ρ.

It seems unlikely that the behaviour could reflect an *E*2 mechanism, because of the similarity of measured elimination rates and expected ionisation rates (Figure 1), and because of evidence from small leaving-group effects, in the following paper,[11] that elimination of 9-halogeno-9,9′-bifluorenyls, and thus also, presumably, of the corresponding benzoates ($\rho = 0.72$), is *E*1cB. The remote possibility of a reversible *E*1cB mechanism is excluded by observation of general base catalysis and lack of buffer-saturation in trimethylamine buffers up to concentrations of 0.75M-Me_3NH^+, and by measurements of primary isotope effects of 6.4 and 7.8 (±1.3) for elimination of fluoren-9-ylmethyl 3-chloro- and 4-methoxy-benzoates, respectively. The measured isotope effects bracket the range of values (6.3—6.8) observed for authentic fluorene ionisations.[1,2,13]

Table 5. Rate-depressing effects ($k_{HH}/k_{R^1R^2}$) of α-substituents upon carbanion formation of fluorene derivatives ($BiphCHCR_1R_2X$) at 25° in NaOMe–MeOH

R¹,R²	OH	OAc	OBz
H,H	1	1	1
H,Ph	5.6	8.2	6.4
H,Me		7.3	8.5
H,Bu^t			6.5
Biph [a]		159	59
Me,Me	44	1 110	923

[a] Biphenylyl.

Assignment of an irreversible *E*1cB mechanism is consistent with the proven reaction path for elimination of 1-(1-acetoxy-1-methylethyl)indene (10).[24] In methanol solvent this substrate undergoes competing elimination and 1,3-rearrangement in the presence of amine bases or methoxide ion. Thibblin and Ahlberg have shown by an elegant combination of kinetic and product isotope measurements that the two reactions proceed *via* a common carbanion intermediate.[24,36] The rate constant for elimination is very similar to that for 9-acetoxymethylfluorene (0.016 compared with 0.043 l mol^{-1} s^{-1}) and the substrates resemble each other structurally, in pK_a, in ρ^* for ionisation (Table 4), and in primary kinetic isotope effects.

Substituent Effects.—A further unexpected feature of the carboxylate eliminations is their sensitivity to α-alkyl and aryl substituent effects. It was found previously that rate-retarding effects of α-methyl and phenyl substituents upon ionisation of 9-hydroxymethylfluorene, as measured by tritium isotope exchange, were substantially less than upon elimination of the corresponding chlorides.[10] The difference was ascribed to an *E*2 mechanism of elimination for the chlorides and steric hindrance to double-bond formation. Thus whereas an α-phenyl substituent decreases the rate of ionisation of 9-hydroxymethylfluorene by a factor of 5.6 an α-aryl substituent slows the reversible *E*1cB elimination of the methyl ether by a factor of 30.[37]

For carboxylate leaving groups, in so far as elimination involves rate-determining formation of a carbanion, α-substituent effects might be expected to mirror those of the carbanion-forming isotope exchange of the alcohols rather than of the *E*2 or reversible *E*1cB eliminations. In fact their comparison in Table 5 shows much larger effects for the acetate and benzoate than for the alcohol, at least for the α-dimethyl substituents which dominate the pattern. Two methyl groups decrease the elimination rates by a factor of 10^3, 25 times as much as ionisation of the alcohol and twice as much as elimination of the chlorides.[10]

The behaviour cannot be due to a change in rate-determining step from reversible to irreversible *E*1cB elimination because elimination of the dimethylbenzoate shows a normal primary hydrogen isotope effect of $k_H/k_D = 7.8$ and no indication of isotope exchange competing with elimination when rates are measured in deuteriomethanol. Nor, presumably, can it be due to reaction by an *E*2 mechanism, since if the ionisation rate of the unsubstituted acid is consistent with the correlation of Figure 1 this would imply even larger substituent effects on ionisation than observed and greater effects on ionisation than on *E*2 elimination.

Comparison of phenyl and methyl substituent effects upon ionisation of the alcohol in Table 5 with their effects on unsubstituted fluorenes calculable from Table 3 and illustrated in Figure 1 however, shows that, as is normal for Taft substitu-

Table 6. M.p.s [a] (°) of fluoren-9-ylalkyl alcohols, acetates, and benzoates ($\mathrm{BiphCHCR^1R^2X}$)

R^1,R^2	H,H	H,Me	H,Pr^i	H,Bu^t	H,Ph	Me,Me	Biph [b]
X = OH	95—96	101—102	81—82	87—88	120—121	99.5—101	195—196 [c]
	(94—96) [d]	(102—103) [e]			(121—122) [e]	(99—101) [e]	
X = OAc	85—85.5	Oil			161—162.5	116.5—117.5	203—204 [c]
	(84—85) [f]						
X = OBz	95—96	86—87	95.5—96.5	109.5—110	185—187	69.5—71	223—226

[a] Values from the literature in brackets. [b] *I.e.* 9-(9,9′-bifluorenyl) alcohol, acetate, and benzoate. [c] Ref. 11. [d] C. J. Collins, *J. Am. Chem. Soc.*, 1948, **70**, 2418. [e] C. Courtot, *Ann. Chim.* (*France*), 1915, **4**, 157. [f] P. M. G. Bavin and M. J. S. Dewar, *J. Chem. Soc.*, 1955, 4477.

Table 7. M.p.s (°) of benzoyl-substituted fluoren-9-ylalkyl benzoates ($\mathrm{BiphCHCR^1R^2OOCAr}$)

Aryl substituent	*p*-NMe$_2$	*p*-OMe	*m*-Me	*m*-OH	*m*-Cl	*p*-Cl	*m*-NO$_2$	*p*-NO$_2$
R^1,R^2 = H,H	165—167	99.5—100	75—75.5	157—159	90—90.5	107—108	110—111	140—141
R^1,R^2 = H,Bu^t		124—125			116—117			145.5—146.5
R^2,R^2 = Biph [a]			186—187			225—226		226—227

[a] 9-(9,9′-bifluorenyl) benzoates.

ents, the effects are strongly non-additive. Thus phenyl and OH substituents taken singly accelerate carbanion formation but in combination retard it. The deviation from additivity represents a factor of 17 in reactivity. It is possible therefore that the difference between the alcohol and carboxylate groups with respect to dimethyl substitution is simply a manifestation of this non-additivity.

The point is significant because the smaller substituent effects on ionisation of the alcohol than elimination of the corresponding halides have been taken as evidence of a discontinuity between *E*2 and *E*1cB mechanisms of elimination.[10] It appears that this conclusion may have been premature, and that further investigation of the point will be necessary. At present, however, it does not seem useful to add to earlier discussions of the nature of the mechanistic borderline.[10,38]

Experimental

Synthesis.—Carboxylate esters were prepared from the corresponding alcohols. For fluoren-9-ylmethanol a new preparation was used. Fluorenyl-lithium in ether–hexane was treated with gaseous CH_2O at −40° following Ahlberg's procedure for the corresponding indenyl alcohol.[39] Formaldehyde was generated by heating paraformaldehyde to 200° with a generator linked to the reaction flask by wide-bore (*ca.* 10 mm) polyethylene and glass tubing terminating just above the surface of the solution. Sweeping with a steady pressure of nitrogen limited repolymerisation. The method compares satisfactorily with other preparations of the alcohol and typically 25 g of fluorene gave 15 g of product. Other fluorenylalkyl alcohols were prepared by dropwise addition of the appropriate aldehyde or ketone to fluorenyl-lithium at −30 to −40°.

Substituted benzoate esters were prepared from the corresponding acid chlorides, usually obtained from the acids by reaction with thionyl chloride catalysed by a few drops of DMF;[40] for *p*-nitrobenzoyl chloride, PCl_5 was used.[41] The chloride was added to the alcohol in dry pyridine. The product was taken up in ether, washed with acid, dried, and after evaporation normally recrystallised three times from methanol. For 1-(fluoren-9-yl)-1-methylethyl and 9-(9,9′-bifluorenyl) benzoates low yields only were obtained after reaction for several days; the products were purified by chromatography on silica. M.p.s of alcohols and benzoates are given in Tables 6 and 7 and are uncorrected. Satisfactory analyses and spectra (usually ^{1}H and ^{13}C n.m.r.) were obtained in all cases and are given only for ***fluoren-9-ylmethyl benzoate*** $\delta_H(CDCl_3)$ 4.52 (3 H, m, CH, CH_2) and 7.24—8.25 (13 H, m, ArH), $\delta_C(CDCl_3)$ 46.9 (1 C, s, CH), 67.0 (1 C, s, CH_2), 120—143.7 (18 C, 10s, ArC), and 166.3 (1 C, s, CO) (Found: C, 84.2; H, 5.45. $C_{21}H_{16}O_2$ requires C, 84.0; H, 5.35%).

Acetate and pivalate esters were prepared from the anhydride catalysed by $ZnCl_2$.[39] Fluoren-9-ylmethyl pivalate melted at 61—62°; m.p. of acetates are given in Table 6; again, satisfactory analyses and spectra were obtained.

For asymmetric alcohols and their esters the fluoren-9-yl carbon is prochiral and doubling of lines in n.m.r. spectra was observed in some cases.

A number of carboxylate esters were prepared from 9-deuteriated fluoren-9-ylmethanol, namely [9-^{2}H]fluoren-9-ylmethyl 3-chlorobenzoate, and 1-([9-^{2}H]fluoren-9-yl)-1-methylethyl benzoate. The first two were prepared by isotope exchange and reduction ($LiAlH_4$) of fluoren-9-ylcarboxylic acid methyl ester, the third by reaction of [9,9-$^2H_2$]fluorene with butyl-lithium followed by acetone. Fluorene was deuteriated by quenching of fluorenyl-lithium with D_2O and twice recycling; the greater than 97% deuteriation reflected a favourable isotope effect on reaction of fluorene with butyl-lithium.[37]

Fluoren-9-ylmethyl *NN*-dimethylcarbamate and carbanilate were prepared by reaction of fluoren-9-ylmethyl chloroformate (Aldrich Chemical Co.) with dimethylamine and aniline, m.p.s 79—80 and 188—190° (lit.,[19] 188—190°), respectively, as described by Carpino.[19]

MeOH and MeOD were distilled from magnesium and NaOMe prepared by dissolving sodium (99.9% Pierce Inorganics pure metal grade) in methanol under nitrogen.

Kinetic and Product Analysis.—Kinetics were measured from the increase in absorption due to the dibenzofulvene elimination product.[1,11] Measured second-order rate constants showed minor trends with methoxide ion concentration, typically varying by 10—30% with a ten-fold concentration change. Reported rate constants were derived by linear extrapolation to zero base concentration. Averaged rate constants were also computed and in nearly all cases differed from extrapolated values by <10%. Comparison of ρ values from extrapolated and averaged rate constants for elimination of substituted fluorenylmethyl benzoates gave values of 0.42 and 0.45, respectively.

Fractions of elimination (f_E) for reactions in which competing transesterification was important were estimated from apparent extinction coefficients of the products using equation (2) in which OD_{obs} is the absorbance at $\lambda_{max.}$ for the dibenzofulvene product, C is the concentration of reactant, and ε_R, ε_D, and ε_{LG} are the extinction coefficients of the reactant, the dibenzofulvene, and the leaving-group anion respectively: ε_R is substituted for the sum of the extinction coefficients of the ester and fluoren-9-yl alcohol products of transesterification. Corrections for anion absorbance were appreciable for some substituted benzoates. Extinction coefficients of the vinyl-substituted dibenzofulvenes were measured by assuming quantitative elimination in NaOMe–MeOH of the appropriate fluorenylalkyl halide or tosylate, except for t-butyldibenzofulvene which was isolated as an oil from elimination of the chloride and purified by p.l.c. on silica. Values of the extinction coefficients are as follows [listed as $10^4\varepsilon$ with $\lambda_{max.}$/nm and vinyl substituents, R^1, R^2 in (3), indicated in parentheses]: 7.0 (255; H, H); 3.6 (255; Me, H); 3.0 (257; Ph, H); 4.25 (255; Pr^i, H); 4.35 (257; Bu^t, H); 3.15 (257; Me, Me). For fluoren-9-ylmethyl 3-chlorobenzoate, 250 mg were treated with NaOMe–MeOH and the expected presence of dibenzofulvene, 9-fluorenylmethanol, and methyl 3-chlorobenzoate in the products confirmed by t.l.c. using authentic samples for comparison: no other products were found. Usually, the spectrophotometric product analysis was performed at one base concentration; where the dependence on base was examined, variations in product ratio were within experimental error.

$$f_E = \frac{OD_{obs}/C - \varepsilon_R}{\varepsilon_D - \varepsilon_{LG} - \varepsilon_R} \qquad (2)$$

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