Chlorination of αβ-Unsaturated Carbonyl Compounds. Part II.[1] The Mechanism of Chlorination of *para*-Substituted Methyl *cis*- and *trans*-Cinnamates in Acetic Acid

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The stereochemistry of addition of chlorine or the elements of chlorine acetate to a series of *para*-substituted methyl *cis*- and *trans*-cinnamates in acetic acid has been determined. At least three different mechanisms have been identified; chloronium ion intermediates are favoured with electron-poor olefins, relatively stable and selective ion-pairs predominate with more nucleophilic olefins, and some direct *cis*-addition of chlorine is observed over the entire range. A previous interpretation of the mechanism of chlorine addition to methyl *trans*-cinnamate overestimated the contribution of ion-pair intermediates.

In Part I [1] were described detailed kinetic and product studies on the reaction of chlorine with methyl *trans*-cinnamate in acetic acid. The results appeared to be consistent with, and were interpreted by, a mechanism involving two ion-pairs which collapsed to dichlorides or reacted with solvent to give acetoxy-chlorides.

Because the mechanism of chlorine addition to olefins appears to be a sensitive function of the nature of the substituents on the double bond, it was decided to study the effect of electronic influences in systems in which steric factors could be maintained constant. This paper therefore describes the products and discusses the mechanism of reaction of five *para*-substituted methyl *trans*-cinnamates and three methyl *cis*-cinnamates with chlorine in acetic acid and in acetic acid containing added salts.

RESULTS

All the reactions were carried out by the addition of a freshly prepared solution of purified chlorine in acetic acid, both in the presence and absence of added salts, to a solution of the olefin in acetic acid, such that the initial concentrations were olefin *ca.* 0·01M and chlorine *ca.* 0·1M. The products were not separated individually but were identified from the ^{1}H n.m.r. of the product mixture as described previously.

The ^{1}H n.m.r. spectra of the individual products are in Table 1. They were identified in the manner previously described; [1] from the expected chemical shifts and coupling constants of the dichlorides and acetoxy-chlorides, and by comparison of the spectra with those of the products isolated in the case of the unsubstituted methyl *trans*-cinnamate. In all cases the differences in chemical shift of the α- and of the β-protons between the unsubstituted and substituted products were in close agreement with the differences observed in the corresponding *para*-substituted β-phenylpropionic acids.[2] The differences in chemical shifts of the methoxycarbonyl- and of the acetoxy-proton resonances were of the same order, and in the same direction, as expected.

Only four products were obtained from the chlorination of methyl *p*-nitro-, *p*-chloro-, and *p*-trifluoromethyl-*trans*-cinnamate and from methyl *p*-chloro- and unsubstituted-*cis*-cinnamate. These were the *erythro*- and *threo*-acetoxy-chlorides (I) and (II), and the *erythro*- and *threo*-dichlorides (III) and (IV). The products of chlorination of methyl *p*-methoxy- and *p*-methyl-*trans*-cinnamate and of methyl *p*-methoxy-*cis*-cinnamate depended upon the time of reaction. This was because addition to the double bond is followed very quickly in the presence of an excess of chlorine by substitution in the ring, particularly in the case of the *p*-methoxy-compounds, which also undergo disubstitution.

TABLE 1

^{1}H N.m.r. spectra [a] of reaction products

Substituent	β-CH [c]	α-CH [c]	$CH_3CO\cdot O$	$CH_3O\cdot CO$	$J_{\alpha\beta}$ [b]
erythro-αβ-Dichloro-β-phenylpropionates					
p-NO_2	4·72	5·37	—	6·08	10·3
p-CF_3	4·79	5·41	—	6·12	10·3
p-Cl	4·84	5·42	—	6·12	10·6
p-Me	4·86	5·42	—	6·15	10·8
p-MeO	4·92	5·46	—	—	10·2
3-Cl-4-MeO ...	4·87	5·44	—	6·11	10·5
3,5-Cl_2-4-MeO	4·89	5·45	—	—	10·3
threo-αβ-Dichloro-β-phenylpropionates					
p-NO_2	4·52	5·28	—	6·30	7·3
p-CF_3	4·58	4·34	—	6·34	7·2
p-Cl	4·71	4·36	—	6·36	7·7
p-Me	4·75	4·36	—	6·42	8·2
p-MeO	4·73	—	—	—	—
3-Cl-4-MeO ...	4·74	4·38	—	6·35	8·0
3,5-Cl_2-4-MeO	4·70	4·36	—	6·31	7·2
erythro-β-Acetoxy-α-chloro-β-phenylpropionates					
p-NO_2	3·81	5·40	7·89	6·15	8·2
p-CF_3	3·85	5·42	7·93	6·19	8·2
p-Cl	3·92	5·43	7·94	6·20	8·2
p-Me	3·94	5·44	7·98	6·22	8·5
3-Cl-4-OMe ...	3·96	5·44	7·94	6·19	8·5
threo-β-Acetoxy-α-chloro-β-phenylpropionates					
p-NO_2	—	—	7·82	6·30	—
p-CF_3	—	—	7·85	6·33	*ca.* 8
p-Cl	3·81	—	7·88	6·34	7·3
p-Me.....	—	—	7·91	6·37	*ca.* 8
3-Cl-4-OMe ...	—	—	7·87	—	—

[a] γ-Values ± 0·02. [b] $J_{\alpha\beta}$ in c./sec. ± 0·4. [c] β-Arylpropionic acids: [2] $\tau_{\alpha CH}$: *p*-NO_2 7·30, *p*-Cl 7·41, *p*-Me 7·41, *p*-OMe 7·45; $\tau_{\beta CH}$: *p*-NO_2 6·95, *p*-Cl 7·12, *p*-Me 7·13, *p*-OMe 7·16.

$ArCH(OAc)\cdot CHCl\cdot CO_2Me$ $ArCHCl\cdot CHCl\cdot CO_2Me$

(I) *erythro* (III) *erythro*
(II) *threo* (IV) *threo*

However, the ^{1}H n.m.r. spectra of the ring-chlorinated products were sufficiently different to be estimated separately. After allowance had been made for the ring-substitution, it was apparent that only four addition products were obtained in the initial reaction, corresponding to the

[1] Part I, M. C. Cabaleiro and M. D. Johnson, *J. Chem. Soc.* (*B*), 1967, 565.

[2] T. A. Wittstruck and E. N. Trachtenberg, *J. Amer. Chem. Soc.*, 1967, **89**, 3803.

acetoxy-chlorides and dichlorides (I)—(IV). No side-chain substitution was observed in any reaction, nor was there any evidence of solvolysis of the dichlorides under the reaction conditions. In the Tables of products, therefore, the yields of the unsubstituted and mono- and di-substituted products have been combined, because the relative rates of ring-substitution could be influenced by the nature of the side-chain.

The products of chlorination of all the olefins in the absence of added salts are shown in Table 2, together with

TABLE 2

Products [a] of reaction of substituted methyl *cis*- and *trans*-cinnamates in acetic acid at 20°

p-Subst.	Added salt	No. of expts.	(I)	(II)	(III)	(IV)
		trans-Esters				
MeO	None	3 [b]	0	0	77	23
MeO	0·1M-NaOAc	1	Trace [b]	0	73	24
MeO	0·6M-NaOAc	1	17	Trace	58	22
MeO	1·0M-NaOAc	1	22	Trace	50	26
MeO	1·0M-LiCl	3 [b]	0	0	81	19
Me	None	2 [b]	20	Trace	28	49
Me	0·1M-NaOAc	2	21	Trace	28	48
Me	0·6M-NaOAc	2	32	5	22	41
Me	1·0M-NaOAc	1	46	5	17	32
Me	1·0M-LiCl	1	22	Trace	39	36
H	None	*c*	41	7	12	40
H	1·0M-LiOAc	*c*	49	10	12	30
H	1·0M-LiCl	*c*	40	6	24	30
Cl	None	1	42	5	15	39
Cl	1·0M-NaOAc	1	56	10	10	24
Cl	1·0M-LiCl	1	28	4	35	28
CF_3	None	1	76	8	Trace	16
CF_3	1·0M-NaOAc	1	88	Trace	Trace	6
CF_3	1·0M-LiCl	1	32	4	59	4
NO_2	None	2	81	5	Trace	13
NO_2	0·1M-NaOAc	1	86	Trace	Trace	8
NO_2	0·6M-NaOAc	1	92	Trace	Trace	Trace
NO_2	1·0M-NaOAc	1	91	Trace	Trace	Trace
NO_2	1·0M-LiCl	2	26	Trace	70	Trace
		cis-Esters				
MeO	None	1	0	0	⩾90	⩽5
H	None	1	28	18	43	11
Cl	None	1	24	13	52	11

[a] For estimate of errors, see Experimental section. [b] Includes runs carried out in the presence of trinitrobenzene. [c] From ref. 1. [d] Trace implies ⩽3%.

some of the corresponding results from methyl *trans*-cinnamate.[1] The products obtained in the presence of lithium chloride and lithium acetate are also shown in Table 2.

DISCUSSION

Kinetic Form.—In the *trans*-compounds the *p*-nitro-, *p*-chloro-, *p*-methyl-, and unsubstituted cinnamic acids or methyl cinnamates have been shown to give clean second-order kinetics under the reaction conditions studied here.[3] It is therefore likely that all the reactions are second-order; the only possible exceptions are the *p*-methoxy-olefins, for which the chlorination must be extremely fast (k_{est} *ca.* 10^3 l. mole^{-1} min.$^{-1}$). Since reactions of higher order in chlorine are not usually observed in this solvent except in cases of acid- or halide-catalysis, it is highly probable that this reaction is also second order.

[3] P. B. D. de la Mare and R. Bolton, 'Electrophilic Addition to Unsaturated Systems,' Elsevier, Amsterdam, 1966, p. 84.

Mechanism.—It is immediately apparent, from the changes in products, considered either individually or in pairs, as a function of the change in substituent, that there is no simple trend from *p*-nitro to *p*-methoxy. Therefore, at least three mechanistic variations must be operative over the series.

The possibility of a free-radical chain mechanism was ruled out in the case of the *p*-methoxy- and *p*-methyl-compounds since neither sunlight nor an inhibitor such as trinitrobenzene had any discernible effect. Intrusion of such a mechanism with the less reactive substrates seems highly improbable. Another mechanism that can be ruled out in all cases is one involving acid catalysis similar to that observed with cinnamaldehyde,[4] because the products are only slightly affected by sodium acetate present in sufficient concentration to remove all traces of acid that might be formed either before or during the reaction. It is also unlikely that chlorine acetate is an effective reagent.[1]

Comparison of the product proportions from the *trans*-*p*-nitro- and *trans*-*p*-methoxy-olefins in the absence of added salts shows that the predominant mechanism in the one is quite different from that in the other. It is from the *p*-nitro-olefin that we expect any intermediate carbonium ion to be most unstable. This makes more likely the formation of a cyclic chloronium ion, as has been postulated in the chlorination of the but-2-enes.[5] Such an ion would lead exclusively to the *erythro*-products (*i.e.*, a *trans*-addition of chlorine or chlorine acetate effectively) and, in particular, to considerable solvent participation and hence predominantly to the formation of the *erythro*-acetoxy-chloride. This is largely what is observed; *i.e.*, the *erythro*-acetoxy-chloride is the main product from the *trans*-*p*-nitro-olefin. The small amount of *threo*-acetoxy-chloride could arise through the formation of the stereoisomeric chloronium ion (see Scheme), and the small yield of *erythro*-dichloride through the alternative capture of the chloronium ion by chloride ion. However, the relatively high yield of the *threo*-dichloride [cf. the ratio of (I) to (III)] indicates that there may also be a direct capture of a chlorine molecule through a four-centre transition state or its equivalent. Of these two predominant mechanisms, the chloronium ion path would be expected to be enhanced relative to a less polar direct addition by adding salts to the acetic acid. One thus expects the yield of *threo*-dichloride to be reduced by the presence of salts, though if the *threo*-dichloride is also formed by capture of chloride ion by some intermediate, any reduction would be much smaller in the presence of lithium chloride than sodium acetate. That the yield of *threo*-dichloride is reduced markedly with *both* added salts indicates that it must be formed by a relatively non-polar direct addition. Moreover, the yield of *erythro*-acetoxy-chloride, which is enhanced in the

[4] M. C. Cabaleiro, C. J. Cooksey, M. D. Johnson, B. E. Swedlund, and J. G. Williams, *J. Chem. Soc.* (*B*), 1968, 1026.

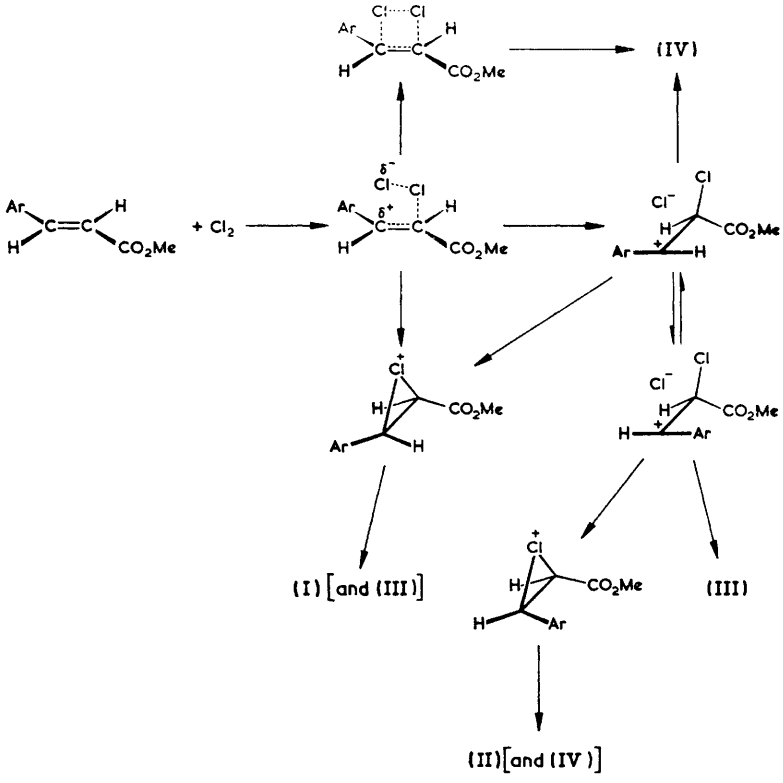
[5] R. C. Fahey and C. Schubert, *J. Amer. Chem. Soc.*, 1965, **87**, 5172.

presence of sodium acetate, is drastically reduced in favour of the *erythro*-dichloride in the presence of lithium chloride, confirming that both of the *erythro*-compounds are formed by capture of the chloronium ion by an external ion.

These two mechanisms will be present to some extent in the closely related reactions of the *p*-trifluoromethyl-olefin, which is very much like the *p*-nitro-olefin, and also in varying amounts in the other cases. Because the decrease in *erythro*-products as a function of increasing electron feed is not monotonic, it is necessary to invoke still a third mechanism which would be most likely to occur in the *p*-methoxy-case, but must also then be considered for cases of intermediate reactivity.

We expect that the potential carbonium ion from the *p*-methoxy-olefin will be considerably more stable than that from the *p*-nitro-olefin, and that there will therefore be far less requirement, if any, for the formation of the cyclic chloronium ion. As the rate of the addition to the *p*-methoxy-olefin is at least some 10^5 times greater than that for the *p*-nitro-olefin, and there are no acetoxy-chlorides at all in the product from the former (clearly shown by the absence of any acetoxy-proton resonance in the crude-product spectrum), it is clear that either a carbonium ion is formed which is so selective that it prefers to react with chloride ion even under adverse conditions of concentration, or that the chloride ion never leaves the close proximity of the ion, *i.e.*, that reaction involves an intimate or solvent-separated ion-pair which collapses to dichloride product. The ion-pair mechanism seems much more likely in view of the known relative nucleophilicities of chloride and acetate and the calculated concentrations of the two species which would be present.

In either case, the carbonium ion must have sufficient life to allow rotation about the C_α–C_β bond effectively to compete with collapse to products, and the proportions of the *erythro*- and *threo*-dichlorides would then depend upon the relative stabilities of the two transition states which should themselves be very close to the relative stabilities of the dichlorides. The greater yield of *erythro*-dichloride is consistent with this hypothesis, but one cannot determine, from the relative yields of dichlorides, how much of the *threo*-dichloride is derived from the ion-pair mechanism and how much is derived from the direct addition. Moreover, in view of the relatively high stability of the ion-pair, one would expect the ion-pair mechanism to be even less facilitated relative to the direct addition by the presence of added salts than is the chloronium ion mechanism. However, though the relative yields of the two dichlorides are unaffected by 1M-lithium chloride, the yield of *erythro*-dichloride is reduced in the presence of sodium acetate in favour of *erythro*-acetoxy-chloride, which indicates that the ion-pair can be captured by the added acetate ion. The added acetate not only provides additional nucleophile but also facilitates separation of any ion-pair intermediates. If a significant proportion of the *threo*-dichloride were formed by the ion-pair mechanism, we would expect its yield also to be decreased in the



presence of sodium acetate, and the yield of the *threo*-acetoxy-chloride to be considerably increased. In fact, only about 1% of *threo*-acetoxy-chloride is formed in the presence of sodium acetate, and the yield of *threo*-dichloride is virtually unaffected. Our evidence thus indicates that a substantial part of the yield of *threo*-dichloride arises through a direct addition relatively uninfluenced by added salts.

Since we can identify at least three mechanisms in the compounds of greatest and least reactivity, it seems likely that the same mechanisms will be evident in the reactions of compounds of intermediate reactivity. Thus, we can expect the ion-pair mechanism to develop into the chloronium ion mechanism as the reactivity decreases, and, as the direct addition is important at both extremes, we may expect it to be important throughout.

The observed product proportions are consistent with this hypothesis. For example, the yield of *erythro*-acetoxy-chloride, which is formed largely through the salt-dependent chloronium ion mechamism, is enhanced by the addition of sodium acetate and is reduced in favour of the *erythro*-dichloride by added lithium chloride in all cases. The yield of the *threo*-dichloride is a maximum from the *p*-methyl-olefin, and must arise mainly from a direct addition since lithium chloride and sodium acetate reduce the yield by almost identical amounts.

The source of the *threo*-acetoxy-chloride is less certain. However, as the yield is highest from the olefins of medium reactivity, it seems reasonable that the formation of the chloronium ion may follow the formation of the ion-pair, and that the carbonium ion stability will be sufficiently great so that the rate of rotation about the carbon–carbon bond and the rate of reaction with solvent and chloride ion are critically comparable. Thus, a second chloronium ion may be formed after rotation about the C–C bond has occurred; this would lead to the *threo*-acetoxy-chloride. In these cases, the addition of salts may stabilise the carbonium ion-pair sufficiently for the rates of collapse relative to internal rotation to shift considerably, and a precise description of mechanism must be more speculative.

If the above mechanisms are a good description of the system, we should be able to rationalise the products observed in the limited experiments on the *cis*-olefins, though with due modification because of the different degrees of non-bonded interactions in the initial and transition states. Thus, the amount of *threo*-products that would arise from a chloronium ion mechanism is less for *cis*- than the amount of *erythro*-products that would similarly arise from the corresponding *trans*-compounds, because the former would give intermediates with greater conformation interaction.

The *cis*-*p*-methoxy-olefin gives almost exclusively the *erythro*-dichloride, which is to be expected because both ion-pair and direct addition (the two predominant mechanisms in the *trans*-*p*-methoxy-case) give this product. This strengthens our belief that much of the *threo*-dichloride from the *trans*-isomer comes from the direct addition, since if it arose from an equilibrium mixture of ion-pair intermediates one would expect a high yield of the *threo*-dichloride from the *cis*-isomer as well. The relatively high yield of the *erythro*-acetoxy-chloride from the unsubstituted and *p*-chloro-*cis*-olefin is consistent with the formation of more than one chloronium ion and/or of ion-pair isomerism. The significant yield of the *threo*-dichloride from these two olefins is also indicative of carbonium ion-pair, for which rotation, chloronium ion formation, and direct collapse to product occur at competitive rates.

The possible routes to the observed products are summarised in the Scheme. It is clear that the initial choice of substrate in Part I,[1] methyl *trans*-cinnamate, was unfortunate, since it appears that in that case all the mechanisms are important and difficult to apportion. The essential difference between the present and the previous interpretation is the proof of participation of the direct addition, which may account for up to 35% of the total reaction.

EXPERIMENTAL

Materials.—Methyl *trans*-*p*-methoxy-, *p*-methyl-. *p*-chloro-, *p*-trifluoromethyl-, and *p*-nitro-cinnamates were prepared by esterification of the corresponding purified acids (obtained from previous work [2]) with diazomethane in ethereal solution.[1] The ethereal solutions were washed with aqueous sodium hydrogen carbonate solution and water, and dried (Na_2SO_4). The ethereal solution was mixed with light petroleum (b.p. 40—60°), evaporated almost to dryness, and the crystalline esters were filtered off. The absence of the corresponding *cis*-esters and of truxinic or truxillic acids in the products was verified from the ^1H n.m.r. spectra in $CDCl_3$. Methyl *cis*-*p*-chloro- and unsubstituted-cinnamate were prepared similarly from the pure *cis*-acids, but the methyl *p*-methoxy-*cis*-cinnamate, which was prepared from a mixture of *cis*- and *trans*-*p*-methoxycinnamic acid, contained *ca.* 20% of the *trans*-ester. M.p. of known esters: *trans*-*p*-methoxy- 90° (lit.,[6] 86°); *trans*-*p*-methyl- 57° (lit., 57—58°,[7] 55—56° [6]); *trans*-*p*-chloro- 76° (lit.,[8] 75—76°); *trans*-*p*-nitro- 154° (lit.,[6] 155—157°); *cis*-unsubstituted, oil. For *methyl* p-*trifluoromethyl*-trans-*cinnamate*, m.p. 72° (Found: C, 57·1; H, 3·9. $C_{11}H_9F_3O_2$ requires C, 57·4; H, 3·9%); *methyl* p-*chloro*-cis-*cinnamate*, m.p. 25° (Found: C, 61·4; H, 4·5. $C_{10}H_9ClO_2$ requires C, 61·1; H, 4·6%).

Chlorination Experiments.—Temperature 20° ± 2°. The ester was dissolved in acetic acid (*ca.* 5 ml.; B.D.H. Aristrar) to which was added a fresh solution of chlorine in acetic acid (45 ml.) containing, where appropriate, added salt, such that the initial concentrations of ester and chlorine were *ca.* 0·01 and 0·10M, respectively. For the very reactive esters, the ester solution was alternatively added to the chlorine solution without significant change in reaction products. In several experiments carried out on methyl *p*-methoxy- and *p*-methyl-*trans*-cinnamates, trinitrobenzene (*ca.* 1 mg. up to saturated) was added to the chlorine solution prior to reaction (see Table 2). After an

[6] G. P. Schiemenz and J. Thobe, *Chem. Ber.*, 1966, **99**, 2263.
[7] V. Prey and H. Berbalk, *Monatsh.*, 1951, **82**, 990.
[8] P. Grünanger and P. V. Finzi, *Gazzetta*, 1959, **89**, 1771.

appropriate interval of from 1 min. for the *p*-methoxy-compounds to *ca.* 3 days for the *p*-nitro-compounds, the solution was poured into water and the crude reaction product was isolated and its ^{1}H n.m.r. spectrum determined as described previously.[1]

^{1}H *N.m.r. Spectra.*—Spectra were measured on a Varian HR 100 spectrometer. The product proportions were determined from the intensities of the methoxycarbonyl- and acetoxy-proton resonances as described previously for the products of reaction of methyl *trans*-cinnamate. In the case of the *p*-methoxy-esters, the *p*-methoxy- and methoxycarbonyl resonances overlapped and it was necessary to determine the proportions of products from the α- and β-proton resonances, and therefore with less accuracy.

Errors in Product Proportions.—The maximum error in the yields of major products quoted in Table 2 is ±4 (actual) % for (III) and (IV) from the *trans*-*p*-methoxy-ester. Errors in the other products vary from ±3 (actual) % for the major products to ±50% of the values quoted for the very minor products.

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