Stereoselectivity and mechanism in the electrohydrodimerisation of esters of cinnamic acid

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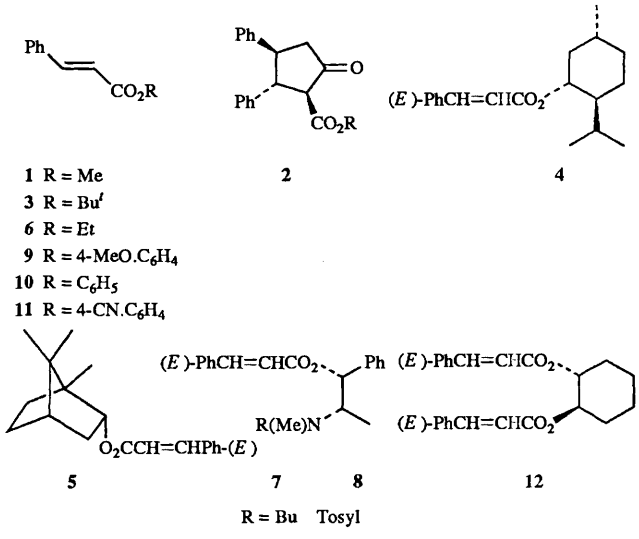
Rate constants (k_{obs}) and reaction orders have been determined for the cathodic reduction in DMF solution of 11 cinnamic acid esters including some derived from chiral alcohols and a dicinnamate derived from *trans*-cyclohexane-1,2-diol. The cinnamic acid esters typically reduce with high stereoselectivity to all-*trans* 3,4-diphenylcyclopentanone-2-carboxylates.† The enhancement of rates of reaction by addition of water was studied for selected substrates and low energies of activation were found. Changes in the alkoxy or aryloxy groups also caused significant changes in rate and log k_{obs} correlated linearly with $E°$ values. The results from kinetic experiments were complemented by product studies of reactions aimed at probing reversibility of key reaction steps. The combined evidence is interpreted as unambiguous support for radical anion–radical anion coupling as the key step with complexation with water, prior to coupling, being crucial.

The relative stereochemistry at C-3 and C-4 is fixed, irreversibly, at the coupling stage and there is strong evidence to suggest that templating in the complex between two radical anions and water determines the stereochemical outcome.

The highly stereoselective nature of the electrohydrodimerisation (EHD) of cinnamic acid esters was first recognised by Klemm and Olson;[1] on cathodic reduction under relatively aprotic conditions [*N*,*N*-dimethylformamide (DMF) containing residual water (< 0.1 mol dm^{-3})], (*E*)-methyl cinnamate **1** gives in almost quantitative yield exclusively a cyclic hydrodimer, methyl (±)-*t*-3,*c*-4-diphenylcyclopentanone-*r*-2-carboxylate **2** (R = Me) in which the ring substituents are all-*trans*.†[1,2] This stereochemistry was first clearly shown[2] by ^{1}H NMR spectroscopy and has since been confirmed[3] by X-ray crystallography. Using chiral auxiliaries it is possible[3,4] to obtain **2** in good to excellent diastereoisomeric excess (de). With the (−)-bornyl ester (*i.e.* with an *endo* linkage) it is possible to achieve[3] > 95% de. In contrast the (−)-menthyl ester gives 0% de. It should be possible to understand the stereoselectivity of these reactions in terms of a precise mechanistic description of the relative importance and sequence of the electron transfer, coupling, protonation and cyclisation steps. The results of a detailed investigation combining precise kinetic experiments with product studies are presented here and the mechanistic uncertainties which are addressed are: (*i*) the nature of the coupling step (radical ion–radical ion or radical ion–substrate); (*ii*) the reversibility or not of the coupling step(s); (*iii*) the reason why cyclisation *via* intramolecular Dieckmann condensation, which happens after only one proton is transferred, competes so favourably with diprotonation to give the linear hydrodimer. Above all, we seek to establish at which stage stereoselectivity is established. There are two aspects to this: (*a*) the exclusive formation in DMF of the all-*trans* cyclic hydrodimers and (*b*) enantioselectivity at C-3 and C-4 for some of the chiral esters.

Consequently precise kinetic measurements have been made for 10 cinnamates and activation energies have also been measured for key examples. The cinnamates chosen (**1** and **3**–**11**) include three simple alkyl esters (**1**, **3** and **6**), four chiral esters (**4**, **5**, **7** and **8**) and in order to extend the reactivity range for the present, predominantly kinetic study, three aryl esters (**9**–**11**). In addition the voltammetry and kinetics of an example of a templated dicinnamate (**12**) have been examined; this is a case where, if the reaction is initiated by transfer of only one electron per molecule, conditions for the observation of the radical ion–substrate route are optimised. The possible effect on stereochemistry of reversibility of the various steps has been probed by testing the stability of possible products under electrolysis conditions and by comparison with base-catalysed Dieckmann condensations.



Results and discussion

Products

For the substrates **1**, **4**, **5**, **7** and **8** preparative electrolyses in DMF have previously been performed[2,3] and in each case the

† A typical example of all-*trans* stereochemistry is given by structure **2**.

Table 1 Reversible potentials for the first reduction of the series of cinnamic acid esters, Ph–CH=CH–COOR, in DMF–0.1 mol dm^{-3} Et_4NBr–0.28 mol dm^{-3} H_2O[a]

R	Me **1**[b]	Bu^t **3**[b]	Menthyl **4**[b]	Bornyl **5**[b]	Et **6**[b]	*N*-(Bu)-eph **7**[b]	*N*-Tos-eph **8**[b]	4-MeO-C_6H_4 **9**[c]	Ph **10**[c]	4-CN-C_6H_4 **11**[c]
E°/V *vs.* SCE	−1.778	−1.833	−1.794	−1.794	−1.789	−1.767	−1.708	−1.654	−1.631	−1.521

[a] Ester concentration 2 mmol dm^{-3} in all cases. Hg/Pt working electrode, T = 22 ± 1 °C. Anthracene used as external reference (see Experimental section). [b] Measured using v = 10 V s^{-1}. [c] Measured using v = 100 V s^{-1}.

corresponding alkyl (±)-*t*-3,*c*-4-diphenylcyclopentanone-*r*-2-carboxylates **2** were obtained in more than 90% yield. The four chiral esters **4**, **5**, **7** and **8**, give rise to products with from 0% de (**4**) to >95% de (**5**).[3] Electrolysis of the additional alkyl cinnamates, **3** and **6** gives the expected alkyl (±)-*t*-3,*c*-4-diphenylcyclopentanone-*r*-2-carboxylates in >90% yield but work-up of electrolysis products of the easily hydrolysed aryl cinnamates is more problematical. However, coulometric experiments indicate smooth 1 F electrolysis and analysis of the crude product mixtures by GC–MS, combined with consideration of their ^1H NMR spectra (see Experimental section) indicates that substantial dimerisation has taken place (65–85% yield). In these cases hydrolysis and decarboxylation may occur on work-up yielding the 3,4-diphenylcyclopentanone, but there is good evidence (GC and NMR) that in contrast to what was found for the alkyl cinnamates both (±) and *meso* isomers are obtained, the ratio of *meso*:(±) increasing in the order **9** < **10** < **11**.

Cyclic voltammetry

The cinnamates **1**, **3**–**11** are easily reduced and cyclic voltammetry in DMF (0.1 mol dm^{-3} Et_4NBr) gives a one-electron reduction peak in the potential range −1.50 to −1.85 V *vs.* SCE and a second, chemically irreversible reduction at lower potentials. The first reduction is chemically reversible at scan rates, v, above 10 V s^{-1} except in the cases of the aryl esters **10** and **11** which required higher scan rates in order to obtain full reversibility. Owing to reproducibility problems for some of the esters (probably caused by adsorption in nominally dry DMF) a fixed amount of water was added to the solution. The potentials, E°, for the first reversible reduction process were determined (see Experimental section) at scan rates where the follow-up reaction was insignificant. The features of immediate interest are that the E° values are significantly influenced by the O-substituent, *i.e.* that derived from the 'alcohol' part of the ester, *cf.* Table 1. Furthermore there is a preliminary indication in the scan rates required to achieve fully reversible reduction that the rates of the follow-up reaction(s) is/are influenced markedly by such substitution; the radical anions derived from the aryl esters are much more reactive than those derived from the simple alkyl esters. At first sight the magnitude of this substituent effect is surprising because any electronic effect on the stability of the first-formed radical anion has to be transmitted through the alkoxy or aryloxy O-atom; the substituents are not directly linked to the delocalised radical anion.

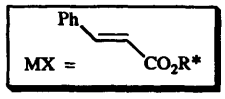
Mechanistic possibilities

The dimerisation reaction indicated by the products may in principle follow either of two major pathways: (*a*) the radical ion–radical ion mechanism in which dimerisation of two radical anions is followed by protonation of the resulting dianion and subsequent Dieckmann condensation [reactions (i)–(iii)] or (*b*) the radical ion–substrate mechanism in which initial coupling of the radical anion with a substrate molecule is followed by further reduction to the dimer dianion and subsequent protonation and Dieckmann condensation [reactions (iv) and (v) and (ii) and (iii)].

For pathway (*a*) the initial coupling (i) or the protonation (ii)

Pathway (*a*)

(i) $2MX^{\bullet -} \underset{k_{-i}}{\overset{k_i}{\rightleftharpoons}} {}^-XM\text{–}MX^-$



(ii) ${}^-XM\text{–}MX^- + HB \xrightarrow{k_{ii}} HXM\text{–}MX^- + B^-$

(iii) $HXM\text{–}MX^- \xrightarrow{k_{iii}} HXM\text{–}M + X^-$

Pathway (*b*)

(iv) $MX^{\bullet -} + MX \underset{k_{-iv}}{\overset{k_{iv}}{\rightleftharpoons}} {}^{\bullet}XM\text{–}MX^-$

(v) ${}^{\bullet}XM\text{–}MX^- + MX^{\bullet -} \xrightarrow{k_v} {}^-XM\text{–}MX^- + MX$

could be the rate-determining step, whereas for pathway (*b*) the reaction between the radical ion and the substrate (iv) or the further reduction (v) could be the rate-determining step. Pathway (*b*) with rate-determining (v) can be distinguished from the other mechanistic possibilities by determination of the combined reaction order[5] in radical ion and substrate which for this case is three when the equilibrium constant for (iv) is small.

Also, pathway (*a*) with rate-determining protonation will be distinguishable by reaction order measurements; if the equilibrium constant for the dimerisation reaction (i) is large, rate-determining protonation will lead to a combined reaction order in radical ion and substrate which is equal to one.[6]

The remaining two possibilities, pathway (*a*) with rate-determining dimerisation (i) and pathway (*b*) with rate-determining coupling (iv) will both give reaction orders equal to two.

Reaction orders

These were measured by derivative cyclic voltammetry (DCV) by determining the scan rate (v_x) required to achieve a certain degree of conversion, $R_I' = x$, as a function of substrate concentration, where R_I' is equal to the ratio between the derivative peak currents in the reverse and forward voltammetric scan.[5] Depending on the overall rate of reaction of the radical anion of the cinnamate, $v_{0.5}$, $v_{0.6}$ or $v_{0.7}$ was chosen. The results are summarised in Table 2.

Within the limits of experimental error (± 10%), reaction orders of two are observed for most of the cinnamates, *cf.* Table 2. The measurement of the reaction order for the 4-cyanophenyl ester **11** is not so clear-cut and at concentrations higher than *ca.* 1 mmol dm^{-3} the reaction order falls below two which may indicate a transition from the dimerisation (i) to the protonation (ii) in pathway (*a*) as the rate-determining step.[6,7] The implications of this particular result are explored in a later section. The results overall at least rule out pathway (*b*) with rate-determining second electron transfer (v) as a possibility, but do not make the crucial distinction between pathway (*a*) with rate-determining (i) and pathway (*b*) with rate-determining (iv). This distinction has been made on the basis of two unrelated experiments, linear sweep voltammetry (LSV)

Table 2 Combined reaction order of substrate and radical anion, $1 + d\log(v_x/V\ s^{-1})/d\log(C°/mmol\ dm^{-3})$, for the series of cinnamic acid esters, Ph–CH=CH–COOR in DMF–0.1 mol dm^{-3} Et_4NBr–0.28 mol dm^{-3} H_2O determined by DCV[a]

R	Me **1**[b]	Bu^t **3**[c]	Menthyl **4**[c]	Bornyl **5**[c]	Et **6**[b]	*N*-(Bu)-eph **7**[d]	*N*-Tos-eph **8**[e]	4-MeO-C_6H_4 **9**[f]	Ph **10**[g]	4-CN-C_6H_4 **11**[h]
Reaction order	2.21	2.00	1.90	1.93	2.21	2.11	2.09	2.14	2.04 ± 0.05	1.80

[a] Hg/Pt working electrode, $T = 23 \pm 3$ °C. [b] $C° = 2, 4, 8$ mmol dm^{-3}, $v_x = v_{0.6}$, $E° - E_{sw} = 0.3$ V. [c] $C° = 2, 4, 8$ mmol dm^{-3}, $v_x = v_{0.7}$, $E° - E_{sw} = 0.3$ V. [d] $C° = 2, 4, 8$ mmol dm^{-3}, $v_x = v_{0.7}$, $E° - E_{sw} = 0.3$ V, Pt working electrode. [e] $C° = 1, 2, 4, 8$ mmol dm^{-3}, $v_x = v_{0.7}$, $E° - E_{sw} = 0.3$ V. [f] $C° = 1, 2, 4$ mmol dm^{-3}, $v_x = v_{0.6}$, $E° - E_{sw} = 0.25$ V. [g] $C° = 1, 2, 4, 8$ mmol dm^{-3}, $v_x = v_{0.6}$, $E° - E_{sw} = 0.3$ V; average of six independent experiments. [h] $C° = 0.5, 1, 2, 4$ mmol dm^{-3}, $v_x = v_{0.5}$, $E° - E_{sw} = 0.25$ V.

Table 3 Linear sweep voltammetric results for phenyl cinnamate **10**[a]

v/V s^{-1}	$E_{p/2} - E_p$/mV	$-dE_p/d\log v$
0.1	41.7	
0.2	42.2	17.4 mV/decade
0.5	44.6	
1.0	47.1	

[a] 8 mmol dm^{-3} **10**, DMF–0.1 mol dm^{-3} Et_4NBr–0.28 mol dm^{-3} H_2O, Hg/Pt working electrode, $T = 23 \pm 1$ °C.

measurements on the relatively reactive phenyl ester **10** and a cyclic voltammetric and double potential step coulometric (DPSC) examination of the reactivity of the dicinnamate **12**, which is structurally similar to the alkyl esters.

LSV experiments

Earlier studies[8] using linear sweep voltammetry and related theory[9] concerning the shifts in peak potential as a function of sweep rate, suggested that for methyl **1** and ethyl cinnamate **6** in DMF containing 5–10% water the rate-determining step was the initial coupling of radical anions, pathway (*a*), and not rate-determining attack by a radical anion on the unreduced substrate, pathway (*b*). Under the conditions considered in our study the rate of reaction of the radical anions derived from the simple alkyl cinnamates is not sufficiently high to be under purely kinetic control[9] as required for the application of 'LSV-slopes' for mechanistic assignments. Even the much more reactive phenyl cinnamate **10** is only approaching purely kinetic conditions at high concentrations (8 mmol dm^{-3}) and low sweep rates (0.1–1.0 V s^{-1}), the conditions to which the results in Table 3 relate. The most conclusive result in Table 3 regarding the mechanism comes from the determination of the half-peak width, $E_{p/2} - E_p$. At the highest sweep rate (1 V s^{-1}), the conditions least amenable to application of the LSV theory, a value of 47.1 mV is found which is significantly below the value of 58.3 mV predicted for the rate-determining radical anion–substrate coupling under purely kinetic conditions. At the lowest sweep rate (0.1 V s^{-1}) the $E_{p/2} - E_p$ value found, 41.7 mV, is close to the limiting value of 38.8 mV demanded by theory for rate-determining radical anion–radical anion coupling under purely kinetic conditions. Deviations from purely kinetic conditions, slow electron transfer or uncompensated *iR*-drop in solution would all lead to artificially *larger* half-peak widths. At the same time the experimental value of $-dE_p/d\log v = 17.4 \pm 0.7$ mV, measured at 8 mmol dm^{-3} and using sweep rates between 0.1 and 1 V s^{-1}, is in adequate agreement with the limiting value, 19.7 mV, expected for rate-determining radical anion–radical anion coupling under purely kinetic conditions, while pathway (*b*) with rate-determining coupling (iv) would give a value of $-dE_p/d\log v = 29.6$ mV. However, deviations from purely kinetic conditions may give artificially too low values of $-dE_p/d\log v$ and therefore this criterion is not as useful as the half-peak width for mechanistic assignments.

Experiments with the dicinnamate 12

Compelling evidence in favour of the radical ion–radical ion coupling was obtained for this substrate. The dicinnamate **12** was prepared from *trans*-cyclohexane-1,2-diol with a view to templating the two cinnamate functions in a manner which would optimise the possibility of intramolecular coupling. Its reactivity was investigated by cyclic voltammetry (Fig. 1). The two cinnamate groups couple electronically sufficiently for the overall two-electron reduction process to appear at scan rates > 10 V s^{-1} as two closely spaced one-electron waves (Fig. 1A). At 500 V s^{-1} reversibility of both waves is observed which allows the determination of the two $E°$ values of −1.749 and −1.829 V *vs.* SCE, respectively (Fig. 1B). Reversing the sweep on the rising portion of the first wave shows chemical reversibility of this first wave at intermediate sweep rates (*e.g.* 10 V s^{-1}, Fig. 1C) indicating that no fast intramolecular radical ion–substrate coupling takes place. However, at this sweep rate, reversal at the second wave (last trace in Fig. 1C) does not increase the height of the oxidation peak in the reverse scan in contrast to what is observed with *e.g.* ethyl cinnamate, which is shown in Fig. 1D for comparison. Reversing the sweep after the second peak causes both waves to be chemically irreversible, *cf.* Fig. 1A. The conclusion from these qualitative results is that when only one electron per molecule is transferred, the radical ion–substrate reaction does not take place on the timescale of these experiments, but when two electrons are transferred (second wave) a relatively rapid reaction does take place. The simplest explanation is that at the second wave the neighbouring radical ions combine intramolecularly.

In order to verify the feasibility of an intramolecular radical anion–radical anion coupling of the two cinnamate groups, the

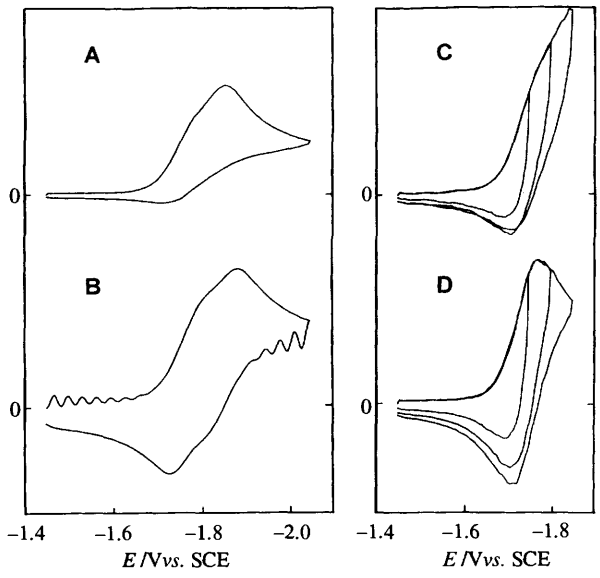


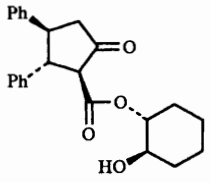
Fig. 1 A: Cyclic voltammogram of 2 mmol dm^{-3} dicinnamate **12** in DMF–0.1 mol dm^{-3} Et_4NBr, Hg/Pt electrode, $v = 10$ V s^{-1}. B: Same solution as in A, but $v = 500$ V s^{-1}. C: Same conditions as in A; the scan reversed at three different potentials 50 mV apart, see text. D: Cyclic voltammogram of 2 mmol dm^{-3} ethyl cinnamate **6** in DMF–0.1 mol dm^{-3} Et_4NBr, Hg/Pt electrode, $v = 10$ V s^{-1}; the scan reversed at three different potentials 50 mV apart, see text.

Table 4 Observed second-order rate constants, k_{obs}, based on the radical anion–radical anion dimerisation mechanism for the series of cinnamic acid esters, Ph–CH=CH–COOR, in DMF–0.1 mol dm^{-3} Et_4NBr–0.28 mol dm^{-3} H_2O determined by DCV[a]

R	Me **1**[b]	Bu^t **3**[c]	Menthyl **4**[c]	Bornyl **5**[c]	Et **6**[d]	*N*-(Bu)-eph **7**[e]	*N*-Tos-eph **8**[f]	4-MeO-C_6H_4 **9**[g]	Ph **10**[h]	4-CN-C_6H_4 **11**[i]
k_{obs}/dm^3 mol^{-1} s^{-1}	(7.8 ± 0.7) × 10^2	(4.1 ± 0.1) × 10^2	(5.4 ± 0.1) × 10^2	(5.6 ± 0.2) × 10^2	(5.4 ± 0.7) × 10^2	(5.8 ± 0.8) × 10^2	(1.6 ± 0.2) × 10^3	(6.1 ± 0.6) × 10^3	(8.1 ± 0.4) × 10^3	(5.7 ± 0.4) × 10^4

[a] Hg/Pt working electrode, T = 23 ± 3 °C. [b] $E^\circ - E_{sw}$ = 0.3 V; k_{obs} calculated by fit to working curve (C° = 0.5, 1, 2, 4, 8 mmol dm^{-3}). [c] $E^\circ - E_{sw}$ = 0.3 V; k_{obs} calculated by fit to working curve and application of $v_{0.7}$ values (C° = 2, 4, 8 mmol dm^{-3}). [d] $E^\circ - E_{sw}$ = 0.3 V; k_{obs} calculated by fit to working curve (C° = 0.5, 1, 2, 4, 8 mmol dm^{-3}) and application of $v_{0.7}$ values (C° = 2, 4, 8 mmol dm^{-3}). [e] $E^\circ - E_{sw}$ = 0.3 V; k_{obs} calculated by fit to working curve and application of $v_{0.7}$ values (C° 2, 4, 8 mmol dm^{-3}), Pt working electrode. [f] $E^\circ - E_{sw}$ = 0.3 V; k_{obs} calculated by fit to working curve and application of $v_{0.7}$ values (C° = 1, 2, 4, 8 mmol dm^{-3}). [g] $E^\circ - E_{sw}$ = 0.25 V; k_{obs} calculated by fit to working curve (C° = 0.5, 1, 2, 4, 8 mmol dm^{-3}) and application of $v_{0.5}$ values (C° = 1, 2, 4 mmol dm^{-3}). [h] $E^\circ - E_{sw}$ = 0.3 V; k_{obs} calculated by application of $v_{0.6}$ values (C° = 1, 2, 4, 8 mmol dm^{-3}); average of 6 independent experiments. [i] $E^\circ - E_{sw}$ = 0.25 V; k_{obs} calculated by fit to working curve (C° = 0.5, 1 mmol dm^{-3}) and application of $v_{0.5}$ values (C° = 0.5, 1 mmol dm^{-3}).

combined reaction order in substrate and di(radical anion) of the dicinnamate **12** was measured by DPSC which involved stepping to a potential negative of the second electron transfer (see Experimental section). At concentrations in the range 0.5–8 mmol dm^{-3} the reaction order was close to one (1.09) indicating intramolecular radical ion–radical ion coupling in preference to second-order reactions. It is therefore possible to conclude that when favoured by intramolecularity the radical anion–radical anion takes place while the radical ion–substrate coupling does not. Preparative-scale electrolysis gave the product **13** expected of the intramolecular reaction.



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The rate constant for intramolecular reaction of **12** was measured at several concentrations in the range 0.5–8 mmol dm^{-3} (Experimental section) and was found to be 220 s^{-1}. The enhancement in the rate of coupling caused by the templating may be estimated by comparison with the reactivity of ethyl cinnamate (see below, Table 4, k_{obs} = 540 dm^3 mol^{-1} s^{-1}). The maximum concentration of the ethyl cinnamate radical anion which can be involved in coupling is the substrate concentration at which the measurements are made; using a concentration of 2 mmol dm^{-3} allows an estimate of 540 dm^3 mol^{-1} s^{-1} × 0.002 mol dm^{-3} = 1.1 s^{-1} to be made for a corresponding first-order rate constant. Because a maximum concentration of radical anion is assumed the implied enhancement of *ca.* 200 is likely to be a conservative estimate. Alternatively the ratio of the two rate constants gives the enhancement in the form of an effective molarity,[10] *i.e.* 220 s^{-1}/540 dm^3 mol^{-1} s^{-1} = 0.4 mol dm^{-3}.

Kinetics

***(a)* Effect of structure.** The rate constants for dimerisation are summarised in Table 4; they were determined on the basis of pathway (*a*) with the radical anion–radical anion coupling [reaction (i)] as the rate-determining step, as confirmed above; see the Experimental section. The effect of structure on rate is marked with a 140-fold difference being observed between the rate constants for the slowest (**3**, R = Bu^t) and the fastest (**11**, R = 4-NC-C_6H_4) reacting esters. That the small change in structure from ethyl cinnamate to methyl cinnamate increases the rate of dimerisation has previously been observed.[7,8]

The effect of structure on rate is related to its effect on E° values in a remarkable way which is expressed as the linear plot in Fig. 2. A similar relationship has been observed[11] for the dimerisation of dithiin radical cations.

Table 5 Effect of increasing water concentration on the observed rate of reaction of the radical anion derived from methyl cinnamate **1** and phenyl cinnamate **10** in DMF–0.1 mol dm^{-3} Et_4NBr determined by DCV[a]

Concentration of added water/mmol dm^{-3}	4 mmol dm^{-3} **1** $v_{0.6}$/V s^{-1}	4 mmol dm^{-3} **10** $v_{0.6}$/V s^{-1}
0	0.663	8.23
55	0.883	9.00
110	1.06	9.65
280	1.48	11.7

[a] $E^\circ - E_{sw}$ = 0.3 V, T = 26 ± 1 °C. DMF with supporting electrolyte passed through a column of neutral Al_2O_3 before addition of substrate.

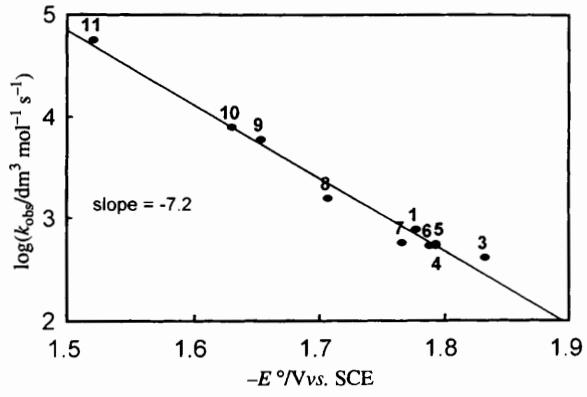


Fig. 2 Plot of the logarithm of the observed second-order rate constants, k_{obs}, for dimerisation of the radical anions derived from the series of cinnamates (data from Table 4) *vs.* the reversible reduction potentials, E°, for the same series of compounds (data from Table 1). The labelling of the points corresponds to the numbering of the different compounds. The line was determined by linear regression (r = 0.991).

***(b)* Effect of water concentration.** The necessity of adding a known amount of water to minimise complications from adsorption has been referred to in relation to measurements of E° values (above) and these conditions (0.28 mol dm^{-3} H_2O) were used throughout for kinetic measurements. It was observed that the addition of water to nominally dry electrolyte (DMF–0.1 mol dm^{-3} Et_4NBr) had a significant rate-increasing effect. The enhancement of rates of EHD reactions by added water are well documented[8,12–18] and explanations have been offered in terms of both general and specific solvation as well as more well defined radical anion–water complexes.

The initial concentration of water in the electrolyte is not known, but the effects on rates of systematically adding known amounts of water are summarised in Table 5, where the value of $v_{0.6}$ is directly proportional to the second-order rate constant, k_{obs}. There is a significant difference between the sensitivity of the observed rates for methyl cinnamate **1** *vis à vis* phenyl

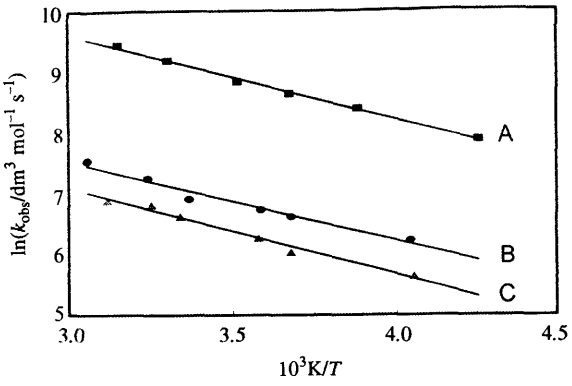


Fig. 3 Arrhenius plots of the dependence of the observed second-order rate constant, k_{obs}, on temperature used for determination of the activation energies. A: 2 mmol dm^{-3} phenyl cinnamate **10** in DMF–0.1 mol dm^{-3} Et_4NBr, 0.28 mol dm^{-3} H_2O; $r = 0.998$. B: 4 mmol dm^{-3} methyl cinnamate **1** in DMF–0.1 mol dm^{-3} Et_4NBr–0.28 mol dm^{-3} H_2O: $r = 0.985$. C: Same conditions as in B except that no water was added; $r = 0.991$. The rate constants were determined at each temperature as described in the Experimental section, and the activation energies are given in the text.

cinnamate **10** which may be regarded as representatives for the alkyl and the aryl cinnamates, respectively. The rate for the faster reacting and more easily reduced substrate, **10**, is influenced less by added water (increased by a factor of 1.4 ± 0.1 from no water added to 0.28 mol dm^{-3} water added) than the slower reacting and less easily reduced substrate **1** (increased by a factor of 2.2 ± 0.1 from no water added to 0.28 mol dm^{-3} water added). The accelerating effect of water on the observed second-order rate constant for dimerisation nicely explains the differences between the value of k_{obs} for ethyl cinnamate **6** reported in Table 4 (5.4×10^2 dm^3 mol^{-1} s^{-1}, DMF, 0.28 mol dm^{-3} H_2O) and those previously reported (1.4×10^2 dm^3 mol^{-1} s^{-1}, dry DMF,[19] 2.25×10^2 dm^3 mol^{-1} s^{-1}, dry DMF[20] and 3.4×10^3 dm^3 mol^{-1} s^{-1}, DMF, 5% H_2O.[8]

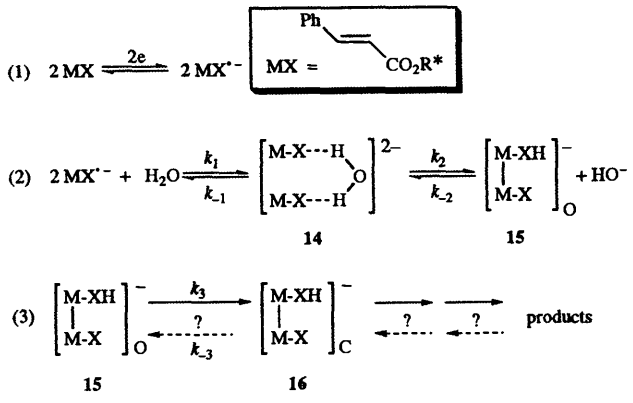
Based on the linear relationship between the $E°$ values and the log k_{obs} values it seems reasonable to assume that also the rate enhancement caused by added water is changing smoothly within the series of substrates. As a consequence, the steepness of the linear regression line of log k_{obs} *vs.* $E°$ is expected to depend on the water content in the DMF. Since water seems to attenuate the structurally related differences in k_{obs} and since the data in Fig. 2 were obtained in the presence of 0.28 mol dm^{-3} H_2O a steeper regression line would be expected had the data been obtained in the absence of added water. We will return to the mechanistic consequences of the water acceleration in a later section.

(*c*) **Effect of temperature (energies of activation).** Observed second-order rate constants for the reductive coupling of the methyl **1** and phenyl **10** esters were measured at a variety of temperatures in the range −30–50 °C and the results are given as Arrhenius plots (Fig. 3). The energies of activation are small and similar for the two esters (11.6 ± 0.3 kJ mol^{-1} for the phenyl ester **10** and 10.9 ± 0.9 kJ mol^{-1} for the methyl ester **1**). In the absence of added water the activation energy for the methyl ester was found to be slightly increased to 12.1 ± 0.8 kJ mol^{-1}.

The overall rate of the reductive dimerisation of the cinnamates is relatively low (Table 4) and the combination of slow reactions and low energies of activation is a strong indication of the involvement of an equilibrium prior to the rate-determining step,[20–27] which in this case is the slow coupling. The observed rate constants are governed therefore by both the position of an equilibrium and the rate of dimerisation of the product of the equilibrium, with the temperature affecting the two components in different directions. Given the significant effect of water concentration on the observed rates it is likely that the proposed pre-equilibrium involves complexation between the initially-formed radical anions and one or more water molecules. Similarly low energies of activation have previously been reported for EHD reactions as well as for dimerisations initiated by electrochemical oxidation.[11,20,26,27]

Conclusions: the early steps

It is convenient at this point to summarise the evidence concerning the nature of the early steps, *i.e.* those leading up to the Dieckmann condensation. In essence we can postulate with some confidence that initial electron transfer gives relatively long-lived radical anions which react further by dimerisation and not by attack on the starting material (substrate). Furthermore, the noticeable effect on rate of added water combined with the low energies of activation for the overall coupling process indicates that it is water-complexed radical anions which dimerise. These steps are outlined in Scheme 1.



Scheme 1 The early steps

It must be remembered that the mechanism finally proposed must also account for the exclusive formation of the (±)-*t*-3,*c*-4-diphenylcyclopentanone-*r*-2-carboxylates **2** derived from (±)-coupling of two radical anions. In the absence of specific interactions, such as hydrogen-bonding, a *meso* form is usually slightly more stable than the corresponding (±) form.[28–30] It might therefore be expected that the coupling of two radical anions of the cinnamates would give the dimeric dianion predominantly as the *meso*-isomer; subsequent Dieckmann condensation would then lead to the (±)-*t*-3,*t*-4-diphenylcyclopentanone-*r*-2-carboxylate **18** with *cis*-configuration of the two phenyl groups in contrast to the observed exclusive formation of the isomer with *trans*-configuration **2**.

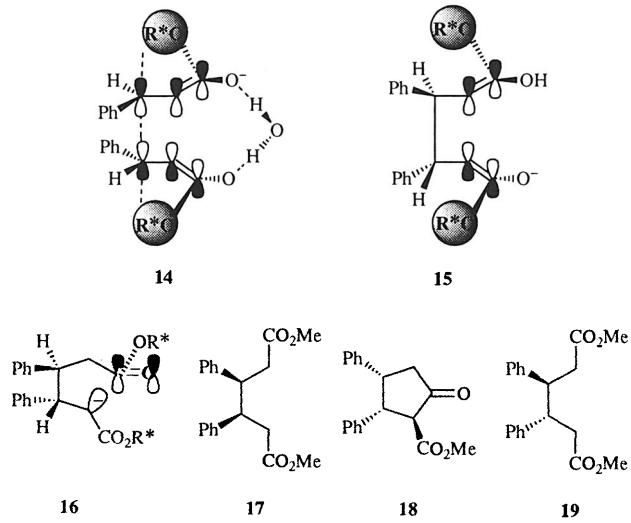


Table 6 Test for reversibility under preparative conditions

Entry	Reactants	Conditions	Product yields (%)
1	**1** (2.6 mmol) + *meso*-dimethyl 3,4-diphenylhexanedioate **17** (1.3 mmol)	Electrolysis,[a] 1.5 F	Total yield 65%: **2** 50, **18** 31, **17** 19
2	**1** (0.63 mmol) + **2** (1.9 mmol)	Electrolysis,[a] 2.5 F	Relative yields (%):[b] methyl 3-phenylpropanoate 21, **2** 79
3	**17**	KH–DMF[c]	**18**[d]
4	**2**	MeONa–MeOH, reflux	(±)-Dimethyl 3,4-diphenylhexanedioate **19** 67

[a] As for electrolysis of alkyl cinnamates, charge consumption based on quantity of methyl (*E*)-cinnamate. [b] Relative yields based on GC–MS analysis, in addition to DMF only peaks for the listed products were observed, total yield > 50%. [c] Reaction carried out at *ca.* 0 °C with two-fold excess of KH. [d] GC–MS analysis of crude product extracted into CH_2Cl_2 after aqueous work-up.

The relevance of the early steps to the high stereoselectivity must therefore be emphasised. It is our contention that the complexation with water plays a key role in 'templating' the radical anions prior to dimerisation. Consequently we have assumed at this stage the representation in Scheme 1 whereby hydrogen-bonding to the carbonyl oxygens of two radical anions gives a complex, containing one or more molecules of water, which is more stable for the transition state leading from **14** to the (±) dimer than for the transition-state leading to the corresponding *meso*-isomer. This will only determine the stereochemical outcome if the coupling step is irreversible. Furthermore we need to keep in mind the fact that proton transfer to the dimeric dianion formed from two radical anions will probably initially be to oxygen; for this reason we have proposed that the oxygen-protonated species **15** is first formed with subsequent conversion into the carbanion **16**. The tautomerism to the carbon-protonated carbanion **16** is required for Dieckmann condensation to take place. Although for convenience the dimerisation of **14** is written as being concerted with proton transfer, the equilibrium denoted by k_2/k_{-2} is most likely attained in a stepwise fashion. The kinetics of the dimerisation will be governed by the position of the equilibrium k_1/k_{-1} as well as by the energetics of the combination step; these influences are the origin of the effect of added water (increases the concentration of **14**) and the low energies of activation (the effect of temperature on the position of the equilibrium k_1/k_{-1} and on the forward rate k_2 is in opposite directions).

With these proposals in mind the matter of the reversibility of these steps and those following on the timescale of preparative electrolysis was addressed by following the stereochemical consequences of a series of preparative-scale experiments in which (±)-**19** and *meso*-**17** linear hydrodimers were subjected to Dieckmann condensation under the conditions of electrolysis and the stability of the final cyclic products (**2** and **18**) derived from initial (±)- and *meso*-coupling tested under conditions of electrolysis.

Experiments concerning reversibility

Chemical and electrochemical conversions of the cyclic and linear hydrodimers (**2** and **17–19**), derived from methyl cinnamate, were carried out with a view to determining whether or not isomerisation of *meso*- and/or (±)-isomers, *i.e.* reversibility of the C–C coupling step, could be accomplished under basic conditions and more especially those pertaining to electrolysis.

The results are assembled in Table 6. The electrolysis of methyl cinnamate (**1**, 2 equivalents) in the presence of *meso*-dimethyl 3,4-diphenylhexanedioate (**17**, 1 equivalent) (entry 1) gives products derived from (±):*meso* coupling in a 1:1 ratio. This is exactly what would be expected for conversion of the methyl cinnamate exclusively into **2** as found when electrolysis of **1** is carried out in the absence of **17** with concomitant base-induced conversion of most of the *meso*-dimethyl 3,4-diphenylhexanedioate into **18**. This result, particularly as it is under electrolysis conditions, argues strongly against a situation in which the products, linear or cyclic, can exchange stereochemistry at the 3,4-positions once it is fixed, *i.e.* in the C–C coupling step, and at the same time demonstrates that Dieckmann condensation of the anion derived from the *meso*-coupling would take place had it been formed. The discrepancy between the outcome of the experiment described in entry 1 and that of a similar experiment described in ref. 31 is unclear.

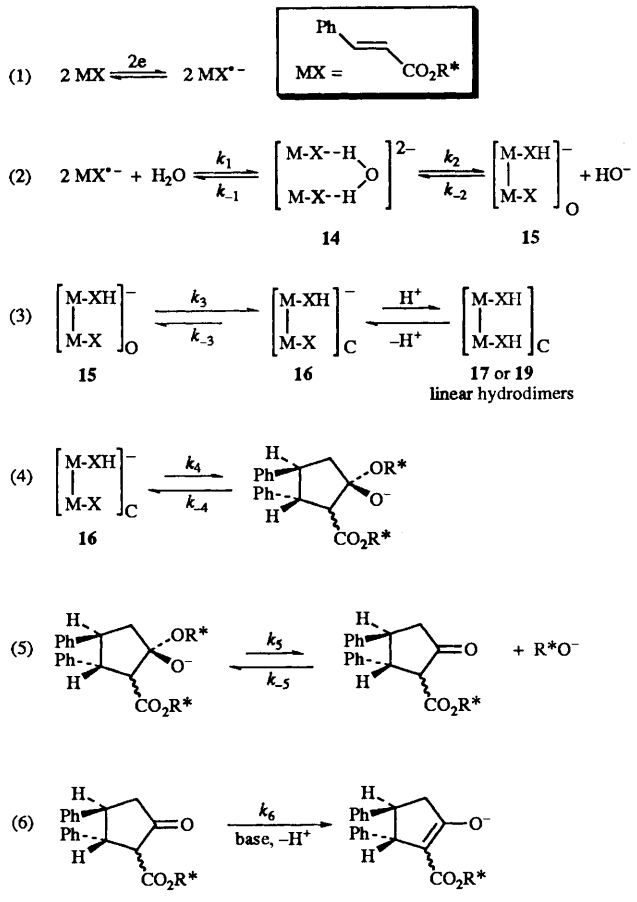
Of the other experiments included in Table 6, entry 2 shows by the cathodic hydrogenation of methyl cinnamate to methyl 3-phenylpropanoate in the presence of **2** that, as expected, the C-2 proton is acidic and under the electrolysis conditions typically used for the cinnamates the product before neutralisation and work-up will be the corresponding anion. It follows that, because the all-*trans* isomer **2** is recovered exclusively, the stereochemistry at C-2 is under thermodynamic control and that the configuration with the C-2 ester group *trans* to the 3-phenyl group is the more stable. Entry 3 concerns a conventional Dieckmann condensation of **17** to give **18** which supports the conclusions drawn under entry 1, *i.e.* the *meso*-dimethyl 3,4-diphenylhexanedioate **17** in the mixed electrolysis is the most likely source of **18**. Finally, the retro-Dieckmann reaction described in entry 4, which gives only (±)-dimethyl 3,4-diphenylhexanedioate **19**, confirms that even under very basic conditions the relative stereochemistry at C-3 and C-4 remains intact; in the absence of specific interactions any reversibility at the C-3 or C-4 position would be likely to give recombination to at least some of the *meso*-isomer **17**.

Finally, there is ample evidence from these experiments that protonation of the dimeric dianion to the linear hydrodimers is reversible. Consequently, even if the linear hydrodimers are formed during electrolysis the conditions are basic enough to give a concentration of the monoanion **16** which allows the Dieckmann condensation to proceed, essentially irreversibly because it gives the stabilised anion of the final product.

Mechanism and stereoselectivity: an hypothesis

The mechanistic features so far established are: (*i*) initially-formed radical anions combine in an overall second-order process and the radical ion–substrate pathway is not involved; (*ii*) the rate-enhancing effect of added water and the observed low energies of activation are well explained in terms of the formation, in a rapidly established equilibrium, of a complex involving two radical anions and water prior to relatively slow coupling; (*iii*) the intramolecular Dieckmann condensation involving the carbanion **16** is reversible but under the basic conditions of electrolysis and of conventional Dieckmann and retro-Dieckmann conditions the stereochemical integrity of the C-3 and C-4 positions was always maintained; (*iv*) before work-up the product is an anion because of the acidity of the C-2 proton, so the stereochemistry at C-2 is determined by thermodynamic control which dictates that the C-2 ester function is *trans* to the C-3 phenyl group.

It follows from these considerations and from the observed formation from the alkyl cinnamates of only the cyclic



Scheme 2 The mechanistic hypothesis

hydrodimers resulting from (±)-coupling that the stereochemistry at C-3 and C-4 is determined at one of the early steps and fixed in subsequent Dieckmann and proton transfer steps. The evidence so far discussed is accommodated by the mechanistic hypothesis presented in Scheme 2. In the light of this proposal other significant features of the reaction may be elaborated, especially the observations of 0–95% diastereoselectivity in the reduction of different chiral cinnamates and the formation of a mixture of *meso*- and (±)-3,4-phenylcyclopentanones in the reduction of the aryl cinnamates (**9**–**11**).

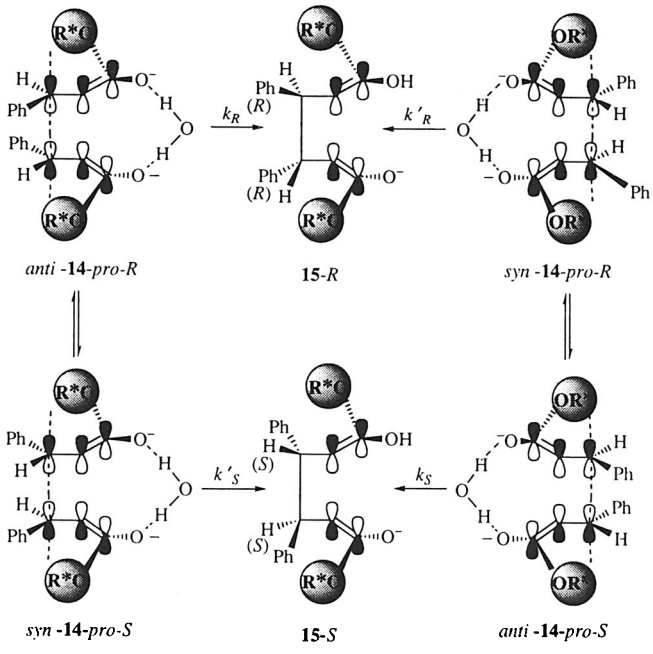
Stereochemistry at C-3 and C-4; the (±):*meso* ratio

The conclusion that this stereochemistry is fixed in an early step requires further explanation. We propose, for the reasons given above, that formation of **15**, or of the dimeric dianion leading to it, is effectively irreversible. Consequently the stereochemistry is determined prior to the C–C bond-forming step, *i.e.* in the complex **14**. In **14** the proposed bridging hydrogen-bonding water molecule combines with the stereoelectronic constraint of orthogonal approach of the radical anions to restrict rotation about the axis of the developing C-3 and C-4 atoms. Thus, in the transition state for C–C coupling the (±) arrangement (staggered) is of lower energy than the *meso* arrangement (eclipsed). Furthermore, there is support for the role of the complex in determining stereochemistry from the different behaviour of the alkyl *vs.* aryl cinnamates (**9**–**11**). The methyl cinnamate **1** gives only (±) coupling and shows a marked dependence of rate on water concentration whereas the rate of dimerisation of phenyl cinnamate radical anions is much less affected by the addition of water (*cf.* Table 5). This is consistent with complexation with water being weaker in the case of aryl cinnamate radical anions which is to be expected from the comparative ease of reduction of the aryl cinnamates, *i.e.* the ester aryl group exerts an electron-withdrawing effect which would lessen the negative charge on the carbonyl oxygens which would therefore be less favourable for hydrogen bonding. Without the constraint on rotation caused by the bridging hydrogen bond the energy difference between the (±) and *meso* arrangements in the transition state for C–C bond formation is lessened and both isomers are formed, the ratio of *meso* to (±) increasing (see the Experimental section) with increasing ease of reduction.

Diastereoselectivity in the chiral esters

Four chiral esters have been included in this study, (−)-menthyl cinnamate **4**, *S*-(−)-bornyl cinnamate **5**, *O*-cinnamoyl-*N*-(butyl)ephedrine **7** and *O*-cinnamoyl-*N*-tosylephedrine **8**.‡ Preparative electrolyses of three of these esters have been described[3] in detail; (−)-menthyl cinnamate **4** gives rise to equal amounts of the diastereoisomers, (0% de), for the product **2**, *S*-(−)-bornyl cinnamate **5** gives one diastereoisomer in high excess (95% de) and *O*-cinnamoyl-*N*-tosylephedrine **8** gives rise to the product **2** with a modest excess of one diastereoisomer (*ca.* 35% de). The *meso*:(±) coupling at C-3 and C-4 is, as explained above, a consequence of different transition-state energies for reaction from distinct complexes of type **14**, say, C-3(*R*)–C-4(*S*) [or C-3(*S*)–C-4(*R*)] *vs.* C-3(*R*)–C-4(*R*) and C-3(*S*)–C-4(*S*). We have seen that for alkyl cinnamates it is the latter pairs which are formed exclusively.

The effect of the chiral auxiliary, R*, in the chiral cinnamates, is to affect the *relative* rates of C–C bond formation to the C-3(*R*)–C-4(*R*) and C-3(*S*)–C-4(*S*) pairs; the situation is complicated by the fact that **14** may exist in two conformations (*syn* and *anti* in Scheme 3) which differ in stability and will there-



Scheme 3 Effect of chiral auxiliaries

fore be present at different concentrations. The *anti* forms will probably predominate for bulky OR* groups. We are now dealing with competing forward reactions governed by the values of k_S, k'_S, k_R and k'_R from a mixture of the *syn*- and *anti*-**14** complexes. We propose that the chiral R* group operates in **14** by interaction with the chiral carbons developing in the transition states at C-3 and C-4. The hydrogen bond templating of the two delocalised radical anions causes the chiral OR* function to be close to the stereogenic C-3 and C-4 atoms (closer

‡ IUPAC names for compounds **7** and **8** are 2-(*N*-butyl-*N*-methylamino)-1-phenylpropyl cinnamate and 2-(*N*-methyl-*N*-tosylamino)-1-phenylpropyl cinnamate, respectively.

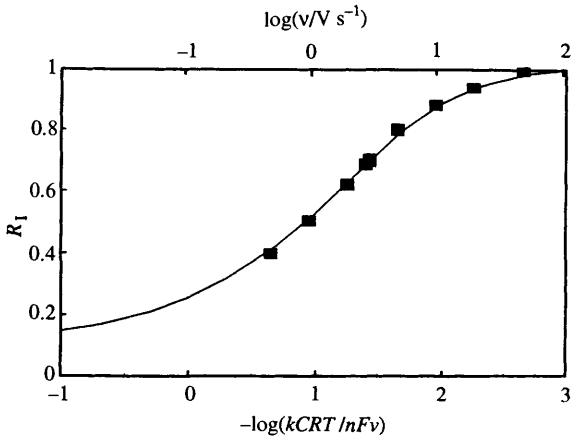


Fig. 4 Fit of experimental data (■, upper x-axis) obtained by DCV on 7.64 mmol dm^{-3} bornyl cinnamate **5** in DMF–0.1 mol dm^{-3} Et_4NBr–0.28 mol dm^{-3} H_2O to theoretical data (solid line, lower x-axis) for pathway (*a*) with rate-determining radical anion–radical anion coupling

in the *syn*- than in the *anti*-complexes) and the chiral groups will influence the two centres equally and in the same direction. Furthermore, the bulkiest group [*S*-(−)-bornyl] would be expected to exert the greatest influence, as is observed.

It is especially noteworthy that the menthyl ester **4** (0% de) and bornyl ester **5** (95% de) are virtually identical with respect to reduction potentials (Table 1) and the values of k_{obs} for the combination of their radical anions (Table 4). According to our model k_{obs} is a function of the overall degree of complex formation and the relative rates of formation of the products, *i.e.* those involving C-3(*R*)–C-4(*R*) and C-3(*S*)–C-4(*S*) bond formation. The products involving *e.g.* C-3(*R*)–C-4(*S*) bond formation are *meso* products and we have seen that these are not formed, at least for alkyl cinnamates. The diastereoselectivity induced by the chiral auxiliary is therefore described in terms of $(k_R + k'_R)/(k_S + k'_S)$, or the inverse, but the observed rate, k_{obs}, is a function of both the position of the equilibrium (k_1/k_{-1} in Scheme 2) of the distribution between *syn*- and *anti*-complexes and of the four k values leading to **15**-*R* and **15**-*S*, *cf.* Scheme 3. We do not have enough information concerning the proposed complexes and individual rates from **14** to **15** but it is in principle possible for the k_{obs} values for the menthyl **4** and bornyl **5** esters to have similar values although their reduction leads to different ratios of **15**-*R* and **15**-*S*.

Experimental

Chemicals

Most solvents were HPLC grade and obtained from Lab-Scan. DMF was distilled under reduced pressure before use. Tetraethylammonium bromide, supplied by Aldrich in 98% purity was stored in a desiccator prior to use. Cinnamoyl chloride, 4-cyanophenol (both 98% purity) and potassium hydride (as a 35% suspension in mineral oil) were also obtained from Aldrich, while 4-methoxyphenol came from Fluka. Methyl and ethyl cinnamates were obtained from Fluka (purum), the methyl cinnamate being recrystallised from methanol before use. The synthesis of the chiral cinnamates has previously been described.[3] The synthesis of the *tert*-butyl cinnamate and the aryl cinnamates were carried out using a similar procedure.[3]

Electrodes, cells and instrumentation

For the kinetic measurements, the electrodes, cells and the electrochemical instrumentation, as well as the measurement and data handling procedures for derivative cyclic voltammetry, linear sweep voltammetry and double potential step chronoamperometry, were identical to those previously described.[32,33]

Determination of E°s

For each of the compounds the E° value was determined as the mid-point between the potential of the reduction peak and the potential of the corresponding oxidation peak. Anthracene was used as an external reference, *i.e.* the E° value for anthracene was determined against the same reference electrode as that used for the series of cinnamic acid esters several times during the series of measurements to monitor the stability of the reference electrode and $E^\circ = -1.92$ V *vs.* SCE for anthracene[34] was used to convert the measured values to the SCE scale. Each of the values given in Table 1 are averages of at least three sets of measurements and the precision of the relative values is *ca.* ± 3 mV.

Kinetic measurements

For each of the cinnamic acid esters the DCV ratio, R_I', was measured over a range of scan rates covering approximately two orders of magnitude from $v = 0.5$ V s^{-1} and upwards. This was done for at least three different concentrations of the esters. At the same time the scan rate at each concentration was fine-tuned to give a value of v_x where $R_I' = x$. Depending on the overall rate of the reaction $v_{0.5}$, $v_{0.6}$ or $v_{0.7}$ was chosen as indicated in the footnotes to Table 2. The values of v_x determined at the different concentrations were used to determine the combined reaction order in substrate and radical anion given in Table 2.

For two of the substrates, **4** and **5**, reproducibility problems due to adsorption at the electrode surface required a slight modification of the usual measurement procedure; instead of waiting 30 or 40 s at the starting potential ($E^\circ + 0.3$ V) between each potential sweep with the cell switched on, the electrode was pulsed to −3.0 V after each scan and the cell disconnected from the potentiostat; immediately before the next scan, the cell was then switched on again. For **7** and **8** the reproducibility was improved by pulsing the electrode to −2.7 V between every change in scan rate. Adsorption of **7** at the usual Hg/Pt electrode made it necessary in this case to use a Pt working electrode.

Rate constants

The observed second-order rate constants, k_{obs}, given in Table 4 were calculated on the basis of theoretical data (obtained by digital simulation, see below) for pathway (*a*) with rate determining radical anion–radical anion coupling (see text). For each of the concentrations the series of experimentally obtained R_I' values were plotted against the logarithm of the scan rate and fitted to the corresponding theoretical working curve as demonstrated in Fig. 4 for the (−)-bornyl cinnamate **5**. Each of these fits gave rise to a value of the rate constant. For each concentration the v_x value used for determination of the reaction order could also be directly converted into a rate constant. The average of the rate constants obtained for each compound is given in Table 4. Owing to the slightly curved reaction order plot for **11** (see text) only the values of the rate constant obtained at the two lowest concentrations were included in the average, since they were judged to represent the 'cleanest second-order' reaction.

Activation energies

In each of the three independent experiments the temperature was kept constant by having the cell immersed in a Dewar flask. The different temperatures were achieved in the Dewar flask by acetone–liquid nitrogen, ice–water, cold water, room temperature and heated water. At each temperature the *iR*-compensation was adjusted. The value of R_I' by DCV was determined as a function of scan rate as described above using $E^\circ - E_{sw} = 0.3$ V in all cases. For each temperature the rate constant was determined by fit of the experimental data to the working curve for the radical anion–radical anion coupling mechanism as described above. The resulting Arrhenius plots are shown in Fig. 3. The slopes, $-E_a/R$, of the linear regression lines of

$\ln(k_{obs}/dm^3\ mol^{-1}\ s^{-1})$ *vs.* $1/T$ (also shown in Fig. 3) were used to calculate the activation energies given in the text.

Kinetic experiments on the dicinnamate 12

The combined reaction order in substrate and di(radical anion) was measured by DPSC by determining the step time ($\tau_{0.4}$) necessary to obtain the ratio $R_1 = -i_b/(i_f 0.2929) = 0.4$ (where i_f and i_b are the currents measured in the end of the reduction and oxidation steps, respectively) as a function of the substrate concentration (0.5, 1, 2, 4 and 8 mmol dm^{-3}). The cathodic step potential was chosen to be *ca.* 0.25 V after E° for the second electron transfer, whereas the anodic step potential was *ca.* 0.3 V before E° for the first electron transfer. For each concentration the $\tau_{0.4}$ value was used to calculate the first-order rate constant for the intramolecular coupling reaction using theoretical data for a simple EC-process, *i.e.* heterogeneous electron transfer (in this case of two electrons) followed by an irreversible first order reaction of the electrogenerated intermediate [here the intramolecular coupling of the di(radical anion)].

Digital simulations

The theoretical DCV response for the rate law determined by the rate determining radical anion–radical anion reaction in pathway (*a*) was obtained by digital simulation using the fully implicit method described by Rudolph[35] using locally developed software as described elsewhere.[36] Any deviations from Nernstian behaviour of the heterogeneous electron transfer were not included in the simulations since preliminary tests showed the influence on the R_1' values to be very small.

GC and GC–MS analysis

A Hewlett-Packard (HP) 5890A gas chromatograph was used attached to an HP5971A MS detector. For GC–MS mode the column was an HP5 (25 m × 0.25 mm id); injection temperature 250 °C, He flow rate 1 $cm^3\ min^{-1}$, temperature held at 50 °C (2 min) then linearly programmed to 300 °C at 10 °C min^{-1}. For GC mode with FID the above conditions were used but with an HP1 column.

Controlled potential electrolysis of *trans*-cyclohexane-1,2-diyl dicinnamate 12

trans-Cyclohexane-1,2-diyl dicinnamate **12** (0.752 g, 2.2 mmol) was electrolysed at a mercury cathode according to the published[3] procedure at −1.6–−1.7 V (Ag/AgBr) in DMF–$LiClO_4$ (0.1 mol dm^{-3}). Under these conditions electrolysis proceeded past the expected point (2 F) but was stopped after passage of 4 F; the relatively high background current is probably due to competing hydrogen evolution. Aqueous work-up with acidification to pH 6 gave a white precipitate which was isolated by extraction into ethyl acetate. Recovery gave a white solid (0.2 g, 33%, mp 185–187 °C) which was identified as the cyclic dimer **13** from the ^1H NMR signals and associated coupling constants characteristic[3] of the *trans*-3,4-diphenylcyclopentanone products.

Controlled potential electrolyses of the aryl cinnamates

An account of the electrolysis of phenyl cinnamate **10** is given, together with details of the product analysis. The same procedures were followed for reductions of 4-methoxyphenyl cinnamate **9** and 4-cyanophenyl cinnamate **11**.

Phenyl cinnamate **10** (0.675 g, 3 mmol) was dissolved in the electrolyte [DMF–Et_4NBr (0.1 mol dm^{-3}), 80 cm^3] in a divided cell equipped with an Hg pool cathode (area 23.8 cm^2), a reference electrode (Ag wire) and a carbon rod anode. The solution was electrolysed at −1.4 V (Ag wire, initial current *ca.* 200 mA) until the current had fallen, after the passage of 1.5 F, to *ca.* 20 mA. The catholyte solution was poured onto ice (*ca.* 400 g), acidified to *ca.* pH 6 (dilute HCl) and the mixture extracted with methylene chloride (2 × 70 cm^3). The methylene chloride solution was washed (water, 5 × 50 cm^3) and dried ($MgSO_4$). Evaporation gave a yellow liquid (1.08 g) which was analysed by GLC with biphenyl as internal standard. From the measured response factor the amount of DMF in the sample (0.51 g) was determined so the amount of residue (0.57 g) indicates an 85% recovery of material. Two peaks in the GLC trace, eluting at 14.9 and 14.8 min (ratio of peak areas 4.6), were identified by subsequent GC–MS analysis as originating from the *meso*- and (±)-3,4-diphenylcyclopentanones or from the corresponding phenyl 3,4-diphenylcyclopentanone-2-carboxylates; the uncertainty in this assignment is because in the mass spectrometer the 3,4-diphenylcyclopentanone-2-carboxylates decarboxylate. However, the ^1H NMR spectrum of the crude product mixture was devoid of the signals at δ *ca.* 4.2 and 3.9 which are characteristic of the 3-H protons in the (±)-*t*-3,*t*-4- and (±)-*t*-3,*c*-4-diphenylcyclopentanone-*r*-2-carboxylates, respectively. Thus it appears that dimerisation with subsequent decarboxylation has taken place.

Furthermore, signals at δ 3.84 and 3.47 were present and correspond to characteristic absorptions[3,37] for the 4-H signals in *meso*- and (±)-3,4-diphenylcyclopentanones, respectively. The absorption at δ 3.47 was the major one and comparison of peak areas indicated a ratio of (±):*meso* = 5.16; this relates well to the ratio of 4.6 found by GLC analysis which makes the reasonable assumption that the detector response factors for the two isomers are equal.

Similar results were obtained for reduction of the esters **9** (at −1.5 V) and **11** (at −1.35 V); according to NMR and GLC analysis both the (±)- and *meso*-3,4-diphenylcyclopentanones were produced from **9** in the ratio 5.5 (GLC) or 2.9 (NMR) and from **11** in the ratio 2.6 (GLC) or 2.3 (NMR).

Reduction of methyl cinnamate 1 in the presence of *meso*-dimethyl 3,4-diphenylhexanedioate 17; Table 6, entry 1

Methyl cinnamate **1** (0.42 g, 2.6 mmol) was electrolysed at −1.55 V (Ag wire) as described for phenyl cinnamate (above) in the presence of *meso*-dimethyl 3,4-diphenylhexanedioate **17** (0.42 g, 1.3 mmol). After the passage of 1.5 F the catholyte was worked up in the usual way to give a solid (0.552 g, 65% recovery of material) which was subjected to GC–MS analysis with the use of an internal standard (dibenzyl ether) indicating a mixture of methyl (±)-*t*-3,*c*-4-diphenylcyclopentanone-*r*-2-carboxylate **2** (R = Me), the isomer **18** and starting material **17** in the proportions given in Table 6.

Reduction of methyl cinnamate 1 in the presence of methyl (±)-*t*-3,*c*-4-diphenylcyclopentanone-*r*-2-carboxylate 2 (R = Me); Table 6, entry 2

Similar electrolysis of methyl cinnamate **1** (0.103 g, 0.63 mmol) in the presence of methyl (±)-*t*-3,*c*-4-diphenylcyclopentanone-*r*-2-carboxylate **2** (0.560 g, 1.9 mmol) gave a colourless liquid (1.68 g) which GC–MS analysis, under conditions known to be able to separate the (±)-*t*-3,*t*-4- and (±)-*t*-3,*c*-4-diphenylcyclopentanone-*r*-2-carboxylates, showed to be a mixture of DMF, methyl 3-phenylpropanoate and **2** as detailed in Table 6; the assumption that the single detected methyl 3,4-diphenylcyclopentanone-2-carboxylate isomer is the all-*trans* isomer **2** rests on the fact that it was in large excess as a starting material and if epimerisation had taken place conversion to the other isomer would not have been complete.

Dieckmann condensation of *meso*-dimethyl 3,4-diphenylhexanedioate 17;[4] Table 6, entry 3

To a mixture of potassium hydride (0.44 g, 3.8 mmol, 35% suspension in oil) in DMF (2 cm^3) was added *meso*-dimethyl 3,4-diphenylhexanedioate **17** (0.17 g, 0.54 mmol). The mixture was stirred at room temperature for 3 h, diluted with cold water and acidified (HCl). The methylene dichloride extract was analysed by GC–MS under conditions known to effect separation of the expected isomeric products. A single peak eluted with m/z 236 (M − CO_2Me). A portion of the extract

was evaporated and the ^{1}H NMR spectrum of the crude product indicated the presence of only methyl (±)-*t*-3,*t*-4-diphenylcyclopentanone-*r*-2-carboxylate **18**; characteristic signals were observed at δ 4.18 (3-H) and 3.6 (CO_2CH_3).

Retro-Dieckmann reaction of methyl (±)-*t*-3,*c*-4-diphenylcyclopentanone-*r*-2-carboxylate 2; Table 6, entry 4

Methyl (±)-*t*-3,*c*-4-diphenylcyclopentanone-*r*-2-carboxylate **2** (0.103 g, 0.35 mmol) was added to a solution of sodium methoxide in methanol (25 cm^3, 0.04 mol dm^{-3}) and heated under reflux for 7 h. After cooling and acidification to pH 6 (HCl) the mixture was shaken with diethyl ether and the ether extract dried ($MgSO_4$). A portion of the extract was analysed by GC–MS using biphenyl as internal standard; (±)-dimethyl 3,4-diphenylhexanedioate **19** was identified (67%). Evaporation of a portion of the extract and ^{1}H NMR spectroscopic analysis of the residue confirmed the assignment through the observation of characteristic signals at δ 3.42 (*cf.* lit.,[37] δ 3.44).

Preparation of *meso*-dimethyl 3,4-diphenylhexanedioate 17

Reduction of methyl cinnamate in methanol leads to formation of a mixture of the two isomers of the linear hydrodimer.[31] Methyl cinnamate **1** (32.4 g, 0.2 mol) was added to the electrolyte [2 dm^3 of MeOH–Et_4NOTs (0.1 mol dm^{-3})] and electrolysed in an undivided beaker cell at an Hg cathode (177 cm^2) with a carbon rod anode. Constant current electrolysis (2.75 A, 0.016 A cm^{-2}) was continued for 4 h. The solution was neutral at the end of the electrolysis and without further treatment methanol was removed under reduced pressure, water added to the residue and the products extracted into diethyl ether (3 × 200 cm^3). The ether extract was dried ($MgSO_4$) and the ether removed to give a yellow liquid to which was added warm methanol (20 cm^3). On cooling *meso*-dimethyl 3,4-diphenylhexanedioate **17** was obtained as white crystals owing to its lower solubility (1.5 g, mp 171–173 °C, lit.,[37] 175–176 °C).

Preparation of *trans*-cyclohexane-1,2-diyl dicinnamate 12

trans-Cyclohexane-1,2-diol (0.58 g, 5 mmol) in dry benzene (3 cm^3) was added dropwise to a stirred solution of cinnamoyl chloride (1.7 g, 0.01 mol) in benzene (5 cm^3). The mixture was stirred at room temperature for 2 days. Removal of the solvent gave a white solid which was recrystallised from ethanol (1.5 g, 80%, mp 81–83 °C); δ_H 1.2–2.2 (8 H, m, cyclohexyl ring *H*), 5.0 (2 H, m, CO_2CH), 6.5 (2 H, d, *J* 16, =C*H*) and 7.5 (12 H, m, Ar*H* and =C*H*).

Preparation of aryl cinnamates 9 and 11

These were prepared in a standard way[3] by the reaction in pyridine between cinnamoyl chloride and the relevant phenol to give 4-methoxyphenyl cinnamate **9** (73%, mp 100–101 °C, lit.,[38] 100–102 °C) and 4-cyanophenyl cinnamate **11** (72%, mp 108 °C); δ_H 6.62 (1 H, d, *J* 16, =C*H*), 7.33–7.73 (9 H, m, Ar*H*) and 7.90 (1 H, d, *J* 16, =CH); (Found: C, 77.0; H, 4.3; N, 5.6. $C_{16}H_{11}NO_2$ requires C, 77.1; H, 4.4; N, 5.6%).

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