Use of readily available monomers in the synthesis of vinyl copolymers with optical activity arising from the configuration of stereogenic carbon atoms in the main chain

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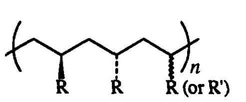
The present work was aimed at synthesising vinyl copolymers with optical activity arising only from the configuration of the stereogenic carbon atoms in the main chain. By copolymerising optically active diesters of fumaric acid with styrene, backbones with a composition of ~2:1 (styrene:fumarate) were obtained displaying strongly negative optical rotations. Cleavage of the optically active alcohol auxiliaries from the side chain yielded corresponding styrene–fumaric acid copolymers displaying a small positive optical rotation. Thus, propagation occurs in these copolymerisations with asymmetric induction to generate a main chain with its own intrinsic asymmetry and corresponding optical activity. The mechanism of the induction is discussed. Corresponding copolymers involving isobutyl vinyl ether (IBVE) or dec-1-ene were synthetically more problematical and this is also discussed.

Introduction

Vinyl polymers with asymmetric main chains may be of interest in terms of their possible piezoelectric, ferroelectric or non-linear optical properties,[1] or as components in liquid crystalline materials. Even in the case of isotactic chains, however, optical activity in vinyl polymers, arising from the configuration of stereogenic carbon atoms in the main chain, usually does not arise because of the inherent symmetry in such molecules. In recent years, however, a number of ingenious strategies have been evolved to ensure asymmetry in all carbon backbone polymers and Okamoto and Nakano have reviewed these recently in a seminal publication.[2] The latter is a remarkably detailed and scholarly piece of work, so much so that it is unnecessary to review all the strategies here. Interested readers are, therefore, directed to that review. Suffice to say that some strategies depend intrinsically on some unusual structural feature *in the monomer* and therefore are not applicable to common vinyl monomers.

In contrast, however, the strategy proposed[3] and subsequently demonstrated[4] by Wulff is based upon derivatives of simple vinyl monomers. Wulff argued that a regularly repeating triad of stereogenic centres **I** in which the first two are of opposite configuration to each other, and the third is randomised or is a completely different structural unit (as in copolymers) would constitute an asymmetric backbone. The resulting polymer would be optically active as a consequence only of the configuration of stereogenic carbon atoms in the polymer main chain. Wulff and Dhal[4] used a chiral template in the form of a bis-4-vinylphenyl boronate derivative of D-mannitol, and polymerised this with various achiral vinyl comonomers. To achieve the required triad placement of stereogenic centres, sufficient of the template comonomer must undergo a regio- and enantio-selective cyclopolymerisation, with the comonomer as the third member of the triad. Remarkably, this does indeed occur and, following removal of the sidechain chiral template and deboronation of the resultant copolymers, optically active styrene copolymers are obtained. Additional examples have been described by Wulff,[5] and the same strategy developed further by Kakuchi, Yokota and co-workers[6] and by Dhal *et al.*[7] using other chiral templates.



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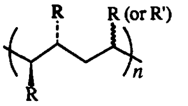


II

This approach has a number of disadvantages however. First, it relies on a selective cyclopolymerisation of a divinyl monomer. Secondly, in some instances the precursor monomer is not commercially available. Thirdly, cleavage of the chiral template does not always yield a readily exploitable optically active polymer. It occurred to us that the regular placement of three stereogenic centres in a repeating triad arrangement could be achieved most easily by copolymerisation of an electron-deficient 1,2-disubstituted alkene with an electron-rich vinyl monomer to produce the well known 1:1 alternating copolymers, **II**, *e.g.* in the copolymerisation of styrene and maleic anhydride.[8] If the 1,2-disubstituted alkene were to carry bulky chiral auxiliaries, there would be a real possibility of enantioselective opening of the double bond during copolymerisation to yield repeating triads closely analogous to those described by Wulff.[3] Subsequent hydrolytic cleavage of the auxiliaries would yield polymers with optical activity arising from the configuration of the carbon atoms in the main chain. In the course of the present work, Dhal *et al.*[9–11] reported a closely related strategy in which achiral maleimides and citraconimides have been copolymerised with styrene derivatives carrying a chiral substituent. The disadvantage of the latter approach is that the precursor styrenes, *p*-vinylbenzaldehyde and *p*-styrylboronic acid, are not commercially available.

We have already made a preliminary disclosure of the results of our work[12] where we have copolymerised optically active diesters of fumaric acid with styrene, which, following cleavage of the chiral auxiliaries, yield an optically fumaric acid–styrene copolymer. We now report, in more detail, the systems we have studied.

Experimental

Materials

All reagents were purchased from the Aldrich Chemical Co. and used as delivered apart from the following. Azoisobutyronitrile (AIBN) and dicumyl peroxide were recrystallised from dichloromethane. Styrene was washed with 10% NaOH and water, dried over magnesium sulfate, distilled at reduced pressure and stored over 4 Å molecular sieves. Isobutyl vinyl ether (IBVE) was distilled at reduced pressure and stored over KOH. Dec-1-ene was distilled at atmospheric pressure and tetrahydrofuran (THF) was distilled from sodium.

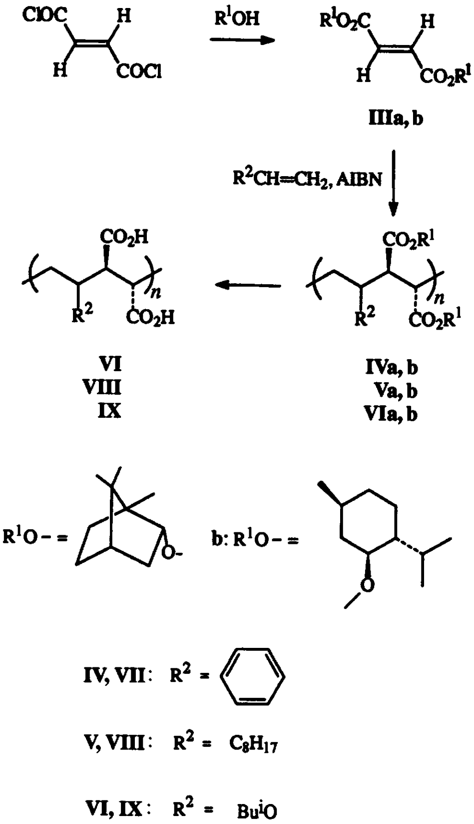
Instrumentation

Infrared spectra were obtained on a UNICAM Matterson 1000 or 6000 FTIR spectrometer. ^1H and ^{13}C NMR spectra were accumulated on a Bruker WM-250 spectrometer at 250 and 62.5 MHz, respectively. Chemical shifts are given in ppm; *J* values are given in Hz. Melting points were recorded on a Gallenkamp melting point apparatus while microanalyses were performed on a Perkin-Elmer CHN 2400 analyser series II. Optical rotations were measured on a Perkin-Elmer 241 Polarimeter in THF using a 10 cm pathlength microcell. Circular dichroism (CD) measurements were recorded on a JASCO J-600 spectropolarimeter in THF employing a 0.2 cm pathlength cell. Polymer molecular masses were determined by gel permeation chromatography (GPC) employing a PLgel 2 x mixed bed-D column (30 cm, 5 µm) with a refractive index detector using THF as eluent at a flow rate of 0.1 ml min^{-1} at room temperature. The columns were calibrated with polystyrene standards.

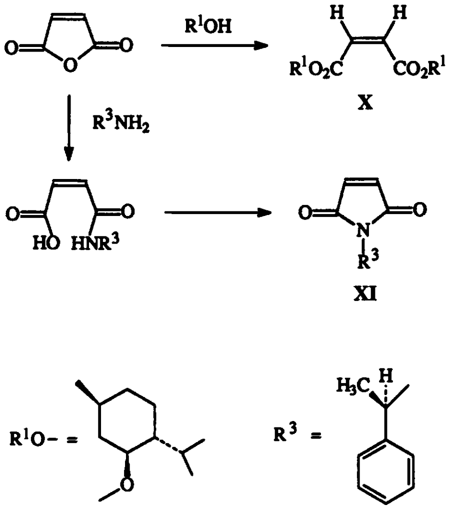
Synthesis of monomers (Schemes 1 and 2)

Di-[(1*S*)-*endo*-(−)-bornyl]fumarate IIIa. (1*S*)-*endo*-(−)-Borneol (51.2 g, 335 mmol) was dissolved in toluene (200 ml) and gently warmed to *ca.* 70 °C under nitrogen. To this stirred solution was added fumaryl chloride (25 g, 165 mmol) and the temperature of the reaction raised only slowly to reflux, in order to keep the reaction from becoming too vigorous. Once at reflux, the reaction mixture was allowed to reflux overnight under nitrogen. The cooled toluene solution was washed with water (3 x 100 ml) and then with 10% NaOH (3 x 100 ml), dried over $MgSO_4$ and evaporated to dryness. The white residue was then crystallised twice from MeOH to afford the desired ester as white flakes (yield = 54%). Mp 109.5–110 °C; ($CDCl_3$): δ_H($CDCl_3$) 0.85 (3 H, s), 0.89 (3 H, s), 0.93 (3 H, s), 0.5–2.6 (16 H, m), 5.02 (2 H, d/t, *J* 3, 10); ν_{max}(KBr)/cm^{-1} 2957, 1719, 1313, 1158, 1022; $[\alpha]_D^{25}$ = −52.3 (*c* 1, THF) (Found: C, 74.6; H, 9.4. $C_{24}H_{40}O_4$ requires C, 74.5; H, 9.4%).

Di-[(1*R*,2*S*,5*R*)-(−)-menthyl]fumarate[13] IIIb. (1*R*,2*S*,5*R*)-(−)-Menthol (51.4 g, 335 mmol) was dissolved in toluene (200 ml) and gently warmed to *ca.* 70 °C under nitrogen. To this stirred solution was added fumaryl chloride (25 g, 165 mmol) and the temperature of the reaction raised only slowly to reflux, in order to keep the reaction from becoming too vigorous. Once at reflux, the reaction mixture was allowed to reflux overnight under nitrogen. The cooled toluene solution was washed with water (3 x 100 ml) and then with 10% NaOH (3 x 100 ml), dried over $MgSO_4$, and the toluene removed under reduced pressure to afford a pale yellow oil. The oil was distilled twice under Kugelröhr distillation conditions (185 °C, 0.01 mbar) to give a colourless viscous oil (yield = 58%). δ_H($CDCl_3$) 0.78 (6 H, d, *J* 7), 0.90 (6 H, d, *J* 7), 0.91 (6 H, d, *J* 6), 1.5–2.4 (18 H, m), 4.85 (2 H, d/t, 4, *J* 10), 6.83 (2 H, s); ν(neat)/cm^{-1} 2990, 1730, 1650, 1460, 1370, 1260; $[\alpha]_D^{25}$ = −96.3 (*c* 1, THF).



Scheme 1 Synthesis of optically active fumarate diesters, copolymerisation with vinyl comonomers and cleavage of chiral auxiliaries



Scheme 2 Synthesis of optically active maleate diester and *N*-aryl maleimide

Di-(1*R*,2*S*,5*R*)-(−)-menthyl]maleate[13] X. (1*R*,2*S*,5*R*)-(−)-Menthol (8.0 g, 50 mmol) and maleic anhydride (2.5 g, 25 mmol) were taken up in toluene (200 ml). The solution was heated until the solution just attained reflux at which point 5 drops of conc. H_2SO_4 were added. The solution was then refluxed vigorously overnight, cooled, washed with 10% NaOH (3 x 100 ml) then water (3 x 100 ml), dried and evaporated to dryness. The resultant oil crystallised on cooling and the solid was recrystallised from methanol to afford white needles (yield = 78%). Mp 97 °C (lit.,[13] 96 °C); δ_H($CDCl_3$) 0.75 (6 H, d, *J* 7), 0.89 (6 H, s, *J* 7), 0.92 (6 H, d, *J* 6), 1.3–2.5 (18 H, m), 4.79 (2 H, d/t, *J* 4, 10), 6.17 (2 H, s); ν_{max}(KBr)/cm^{-1} 2940, 1710, 1450, 1235; $[\alpha]_D^{25}$ = −93.7 (*c* 1, THF).

***N*-(*R*)-(+)-1-Phenylethylmaleamic acid.**[14,15] In a 100 ml two-necked flask provided with a magnetic stirrer, a reflux condenser and a dropping funnel were placed powdered maleic anhydride (4.05 g, 41 mmol) and ether (40 ml). After all the maleic anhydride had dissolved, a solution of (*R*)-(+)-1-phenylethylamine (5 g, 41 mmol) in diethyl ether (4 ml) was added dropwise to the stirring anhydride ethereal solution. The amine was added as rapidly as possible without flooding the condenser. The resulting white suspension was stirred at room temperature for 1 h, the white precipitate isolated by vacuum filtration, washed with diethyl ether and was used without further purification (yield = 94%). Mp 117–119 °C (lit.,[14] 126–127 °C); δ_H($CDCl_3$) 1.55 (3 H, d, *J* 8), 5.10 (2 H, m), 6.19 (1 H, d, *J* 14), 6.58 (1 H, d, *J* 14), 7.28 (5 H, m), 8.84 (1 H, d, *J* 9); ν_{max}(KBr)/cm^{-1} 3252, 3067, 2984, 1719, 1638, 1534, 863, 701 (Found: C, 65.4; H, 5.8; N, 6.4. Calc. for $C_{12}H_{13}NO_3$: C, 65.7; H, 6.0; N, 6.4%).

***N*-(*R*)-(+)-1-Phenylethylmaleimide[14] XI.** In a 50 ml round-bottomed flask provided with a microdistillation apparatus and a magnetic stirrer was placed *N*-(*R*)-(+)-1-phenylethylmaleamic acid (17 g, 78 mmol). The flask was heated at 160 °C for 2 h under vacuum and the water generated removed by distillation. The resultant crude oil was then distilled under Kugelröhr conditions at 150 °C/2 mm Hg to yield a clear oil which was then passed down a short silica column eluting with $CHCl_3$ (yield = 24%). Bp 150 °C at 2 mmHg (lit.,[14] 177–178 °C at 6 mmHg); δ_H($CDCl_3$) 1.78 (3 H, d, *J* 8), 5.31 (1 H, q, *J* 8), 6.57 (2 H, s), 7.25 (5 H, m), 9.32 (1 H, s); ν_{max}(neat) 3111, 3041, 2984, 2956, 1707, 1395, 840, 701; $[\alpha]_D^{25} = +47.3$ (*c* 1, THF) (Found: C, 71.5; H, 5.6; N, 6.8. Calc. for $C_{12}H_{11}NO_2$: C, 71.6; H, 5.5; N, 7.0%).

Polymerisations

Homopolymers. Homopolymerisations of dialkyl maleates and fumarates[16,17] are known to be very inefficient. However, after many failed attempts, fumarates **IIIa** and **b** were homopolymerised by very forcing conditions described as follows for **IIIa**. Diester **IIIa** (2.11 g) and dicumyl peroxide (20 mg) were added to a small glass reactor and all oxygen removed by successive freeze–pump thaw cycles (3 ×). Finally, the reaction was repressurised with argon. The mixture was heated to 120 °C and magnetic stirring started when the system became fluid. Heating was continued until stirring became impossible (*ca.* 3 h). The mixture was cooled, THF added, and the flask vigorously shaken overnight. Insoluble crosslinked polymer (320 mg, *ca.* 15%) was filtered off and the soluble polymer precipitated by pouring the THF solution into methanol (230 mg, *ca.* 11%). Sufficient linear polymer was obtained for ^1H NMR and elemental microanalysis both of which were consistent with the expected structure. Optical rotation measurement yielded $[\alpha]_D^{25} = -41.1$ (*c* 1, THF).

Homopolymer of **IIIb** (770 mg, *ca.* 39%) was similarly obtained from monomer **IIIb** (3.9 g) and dicumyl peroxide (38 mg). $[\alpha]_D^{25} = -58.2$ (*c* 1, THF).

Copolymerisations

Appropriate amounts of fumarates **IIIa** and **IIIb** were dissolved in toluene with the required amount of comonomer (styrene, dec-1-ene or IBVE) according to the feed ratios indicated in Tables 1–4 to yield solutions of comonomers of 2.5 mol dm^{-3}. The initiator, AIBN (1 mass% of comonomers) was added and the solution degassed by freeze–pump–thaw cycles (3 ×). Each mixture was then heated under an Ar atmosphere at the temperature and for the period of time indicated in Tables 1–4. The reaction mixtures were cooled and added dropwise to methanol (*ca.* tenfold excess) at *ca.* 30 °C. The copolymers were recovered by filtration as fine, white powders, which were re-dissolved in THF and re-precipitated into methanol. After drying the products were weighed and the conversion calculated (Tables 1–4). Two precipitations into methanol (*ca.* 30 °C) were found necessary to ensure a negligible level of residual optically active monomer in the copolymer. In the case of fumarate **IIIb** it was possible to recover, purify by double distillation, and re-use the unreacted monomer. For **IIIa** adequate purification proved tedious and synthesis of new batches of monomer proved more convenient.

Hydrolysis of copolymers

Styrene copolymers. Considerable experimentation was required before a suitable hydrolytic procedure was evolved. For example, use of *ca.* 10% KOH in THF under reflux for up to 3 days gave almost no hydrolysis at all. Activation using 18-crown-6, as follows, did, however, prove successful.

Typically, styrene–fumarate copolymer (1 g), freshly ground KOH (1 g) and 18-crown-6 (0.1 g) in xylene (20 ml) were stirred under N_2 at 160 °C until a precipitate of the copolymer carboxylate salt appeared in the initially clear copolymer solution (1–3 days). The precipitate was isolated by centrifugation or filtration, depending on its consistency. It was washed with THF, air dried, and then taken up in water. Acidification of the cloudy aqueous solution afforded a white precipitate which was isolated by centrifugation followed by vacuum filtration. The acid copolymer was re-dissolved in THF and precipitated by addition to chloroform or dilute aqueous HCl. A typical recovery was *ca.* 0.3 g acid copolymer from 1 g parent ester copolymer. Complete removal of the chiral auxiliary was confirmed by ^1H and ^{13}C NMR analysis (see Discussion).

Dec-1-ene copolymers. Hydrolysis of these materials was carried out using the optimised procedure evolved for the styrene copolymers. The isolated fumaric acid–decene copolymers did, however, show some solubility in chloroform, unlike the styrene analogues. ^1H and ^{13}C NMR analysis also was not as definitive (see Discussion).

IBVE copolymers. All attempts to hydrolyse these copolymers produced coloured products—often dark red. Reactions proved very difficult to reproduce and facile decomposition was clearly occurring (see Discussion).

Methylation of fumaric acid copolymers. Methylation of the fumaric acid copolymers was carried out by adding a diethyl ether solution of diazomethane to the acid copolymer in THF until an excess of diazomethane was present (persistent yellow colour). The procedure was essentially as we have already reported.[18,19] The reaction mixture was stirred overnight in a fumehood, during which time the THF and excess diazomethane evaporated. The crude product was re-dissolved in THF, precipitated into methanol, collected and vacuum dried. Typical recoveries of methylated copolymers *ca.* 33%.

Representative styrene and dec-1-ene copolymers were treated in this way, but no attempts were made to methylate the products of the hydrolysed IBVE copolymers because of their excessive degradation.

Results and discussion

Monomer syntheses

Optically-active monomers **IIIa**, **b** and **X** and **XI** were all synthesised in good yield from cheap readily available starting materials. No doubt if these were required in larger quantities the syntheses could be further optimised and the reactions performed readily on a larger scale. Molecular analytical data were consistent with the expected structures, and where previous characterisation data is available in the literature, there is good agreement with our own data.

Polymerisations involving maleate, X, and maleimide, XI

Maleate esters are reported not to undergo homopolymerisation, unless isomerised *in situ* to the corresponding fumarate.[20] This proved to be the case with the dimenthyl maleate, **X**, but somewhat disappointingly it also proved impossible to synthesise any styrene copolymers, and certainly not a 1 : 1 alternating species. In all the attempts made the polymer recovered was essentially homopolystyrene containing dispersed unreacted monomer, **X**.

In contrast, radical copolymerisation of maleimide, **XI**, with styrene readily yielded a ~ 1 : 1 copolymer with a good recovery (*ca.* 98%). The copolymer was soluble in THF, chloroform and toluene, and insoluble in methanol. The broad band at 5.22 ppm in the ^1H NMR spectrum was assigned to the α-proton in the chiral 1-phenylethyl group of **XI**. The copolymer yielded an

Table 1 Synthesis of copolymers **IVa** derived from styrene and the diborneyl fumarate, **IIa**

				Copolymer composition styrene : **IIIa**		Copolymer	
Copolymer **IVa**	Monomer feed; styrene : **IIIa**	Polymerisation[a] conditions t/h (T/°C)	Conversion[b] to copolymer (%)	Elemental microanalysis	^{1}H NMR	$\bar{M}_w$[c]	$[\alpha]_D^{25}$ (c 1, THF)[d,e]
i	1 : 1	15 (80)	39	4 : 3	8 : 5	17 150	−27.5
ii	1 : 1	11 (70)	20	4 : 3	19 : 10	20 600	−27.7
iii	1 : 1	84 (80)[f]	59	—	2 : 1	—	−29.9
iv	1 : 1	84 (80)[f]	24	—	3 : 1	—	−23.6
v	1 : 1	84 (80)[f]	63	—	11 : 5	—	−27.2
vi	1 : 1	84 (80)[f]	59	4 : 3	8 : 5	18 400	−26.1
vii	1 : 1	13 (75)	33	4 : 3	9 : 5	18 450	−28.0
viii	1 : 1	15 (70)	29	4 : 3	19 : 10	23 200	−23.1
ix	1 : 1	11 (80)	35	4 : 3	19 : 10	16 650	−28.2
x	5 : 1	14 (80)	57	4 : 1	2 : 1	15 700	—
xi	10 : 1	14 (80)	>95	6 : 1	4 : 1	27 450	—

[a] 2.5 mol dm^{-3} toluene solutions 1 mol% AIBN, vacuum. [b] Gravimetric. [c] GPC data, polystyrene equivalents. [d] Concentration = 1 g/100 ml 25 °C; [e] Value for homopolymer **IIIa** = −41.1. [f] Different batches of **IIIa** in each case.

Table 2 Synthesis of copolymers **IVb** derived from styrene and the dimethyl fumarate, **IIIb**

				Copolymer composition styrene : **IIIb**		Copolymer	
Copolymer **IVb**	Monomer feed; styrene : **IIIb**	Polymerisation[a] conditions t/h (T/°C)	Conversion[b] to copolymer (%)	Elemental microanalysis	^{1}H NMR	$\bar{M}_w$[c]	$[\alpha]_D^{25}$ (c 1, THF)[d,e]
i	1 : 1[f]	120 (85)	44	—	13 : 5	—	−39.2
ii	1 : 1[f]	120 (85)	42	5 : 3	2 : 1	10 650	−45.1
iii	1 : 1[f]	15 (80)	21	2 : 1	9 : 5	12 750	−44.1
iv	1 : 1[f]	84 (80)	26	3 : 2	11 : 5	13 350	−42.3
v	1 : 1[f]	12 (60)	20	2 : 1	19 : 10	9 645	−41.4
vi	5 : 1	14 (80)	39	6 : 1	4 : 1	17 100	−28.5
vii	10 : 1	14 (80)	>95	8 : 1	5 : 1	22 600	−20.0
viii	1 : 2	14 (80)	>95	4 : 3	—	8 615	−46.6

[a–d] See footnotes Table 1. [e] Value for homopolymer of **IIIb** = −58.2. [f] Different batches of **IIIb** in each case.

$[\alpha]_D^{25}$ value of +27.6, compared with +47.3 for monomer **XI**. This reduction therefore, seems to relate simply to the dilution of the optical group in the 1 : 1 copolymer. This optimistic start soon ended when attempts to hydrolyse the copolymer proved difficult, and indeed this difficulty has already been reported in the literature.[15] Interestingly, Dhal *et al.*[10,11] make no mention of hydrolysing the non-chiral *N*-maleimides they have employed as comonomers with optically active styrenes, whether they attempted this or simply failed, is not clear. We tried numerous procedures, some of which showed clear evidence for opening the imide ring to yield the maleamic acid, but all attempts to hydrolyse the so-formed amide, simply resulted in ring-closure to reform the imide. The chiral auxiliary simply stays doggedly in place in this copolymer.

Styrene copolymers and dibornyl IIIa and dimenthyl IIIb fumarates

The conditions employed and copolymers synthesised are summarised in Tables 1 and 2. Typically the copolymer products are white powders soluble in THF, hexane and chloroform but insoluble in methanol. The elemental microanalytical data is rather insensitive for determining the copolymer composition and the ^{1}H NMR data provides a better indication. The correlation between the two methods, however, is not unreasonable. For a 1 : 1 comonomer feed, styrene and the diborneyl fumarate **IIIa** yield a copolymer with a composition much closer to 2 : 1 (Table 1). This is almost certainly a reflection of the steric bulk of **IIIa**. Even with long reaction times (up to 3.5 d) the maximum conversion obtained was *ca.* 60%. Only by going to higher styrene contents could conversions approaching 100% be achieved. Unfortunately the content of the chiral monomer in the copolymer is then too low to be useful. Overall, however, conversions of 30–50% were not considered too wasteful of chiral monomers. Polystyrene-equivalent (GPC) $\bar{M}_w$ values are *ca.* 16 000–23 000 which seem reasonable for these hindered propagations.

Copolymerisations of styrene with the dimenthyl fumarate, **IIIb**, proved to be more sluggish and conversions were in the range 20–40% for 1 : 1 comonomer feeds, again yielding copolymers with compositions closer to 2 : 1, styrene : fumarate (Table 2). Fortunately some success was achieved in recovering and reusing unreacted **IIIb** and so losses were not too great. Perhaps, not surprisingly, polystyrene-equivalent (GPC) $\bar{M}_w$ data are lower for these copolymers *ca.* 10 000–13 000. A number of batches of both **IIIa** and **IIIb** were used in the course of the work and this in part accounts for the scatter seen in the conversions during copolymerisations and in copolymer properties.

Why the dimenthyl fumarate should be less reactive than the dibornyl one is not clear, especially considering the somewhat flatter geometry of the menthyl group. However, it might be that this factor allows some particular conformer to be favoured by rotations about the ester-*O*-linkage which proves to be sterically unfavourable for radical attack on the double bond. Certainly the lower free radical reactivity of **IIIb** *versus* **IIIa** is also seen in our attempts to produce small quantities of homopolymers of these monomers.

FTIR spectra of the copolymers **IVa**, **b** all feature prominent absorptions at 1730 and 1160 cm^{-1} characteristic of the ester linkage, as well as bands at 2950 and 1453 cm^{-1} characteristic of the styrene residue. The ^{1}H NMR spectra, exemplified in Fig. 1(*a*) by that for copolymer **IVb** iii, are all broad as expected for polymer species. The broad feature at *ca.* 4.5 ppm arises from the proton on the carbon atom α to the ester group in the menthyl (as likewise in the borneyl) residue. The broad resonances due to the styryl aromatic sidechain and the backbone methine and methylene groups are all as anticipated. The aliphatic region is very intense as a result of the contribution from the protons in the menthyl groups. Perhaps most importantly, however, all sharp resonances which would be characteristic of any trapped monomer (**IIIb** in the case of **IVb**) are absent. The corresponding ^{13}C NMR spectrum of **IVb** iii [Fig. 2(*a*)] correlates well with the interpretation of the ^1H NMR spectrum. Overall, therefore, the spectral data confirm that the isolated materials are indeed pure styrene–fumarate copolymers, **IVa, b**, and that the optical rotation data recorded in Tables 1 and 2 are characteristic of the copolymers themselves.

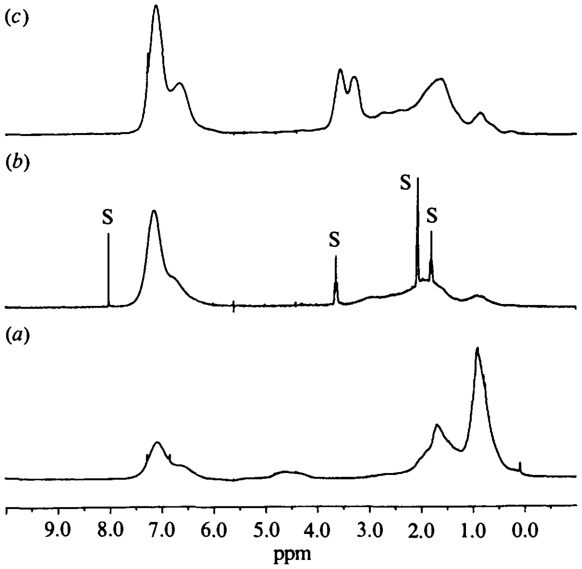


Fig. 1 ^1H NMR spectra of: (*a*) styrene–dimenthyl fumarate copolymer **IVb iii** in $CDCl_3$; (*b*) copolymer **IVb iii** after hydrolytic cleavage of chiral auxiliary in [$^2H_6$]acetone; (*c*) fully methylated styrene–fumaric acid from hydrolysed **IVb iii** in $CDCl_3$ (S = solvent)

Dec-1-ene and IBVE copolymers of dibornyl, IIIa, and dimenthyl, IIIb, fumarates

Data on the dec-1-ene and IBVE copolymers respectively are shown in Tables 3 and 4. In each case, as with styrene, copolymerisations involving the dimenthyl ester were slower than those involving the dibornyl species and, in general, longer reaction times are needed to achieve only modest conversions. Interestingly both dec-1-ene and IBVE as comonomer with a feed ratio of 1 : 1 with either **IIIa** or **IIIb** yield copolymers with a comonomer composition of ~ 1 : 1. This presumably reflects the lower tendency relative to styrene for both dec-1-ene and IBVE to homopolymerise by a free-radical mechanism and for the tendency for alternating propagation to be enhanced accordingly. The lower $\bar{M}_w$ values for the dec-1-ene copolymers compared to the styrene copolymers is also in accordance with this view.

As before, FTIR and NMR spectral data confirmed the absence of unreacted optically active monomer in these copolymers and again therefore the optical rotation data in Tables 3 and 4 refer to the pure copolymers.

Optical activity of styrene IV dec-1-ene V and IBVE VI copolymers with dibornyl IIIa and dimenthyl IIIb fumarates

Generally the sign of the optical rotation of all copolymers is the same as that of the precursor fumarate comonomer, and indeed the respective homopolymers. This indicates that the chiroptical properties are dominated by those of the side chain ester substituents. In all cases the $[\alpha]_D^{25}$ value for the copolymers is less than that of the corresponding fumarate comonomer (Table 5), presumably reflecting the dilution of the optically active comonomer by non-optically active comonomer segments. This effect is seen most clearly for the copolymers of styrene with **IIIb** (Table 2) where copolymers with approximate compositions (styrene:**IIIb**) of 2:2, 3:1, 4:1 and 5:1 are available, as well as the homopolymer of **IIIb**. The variation of

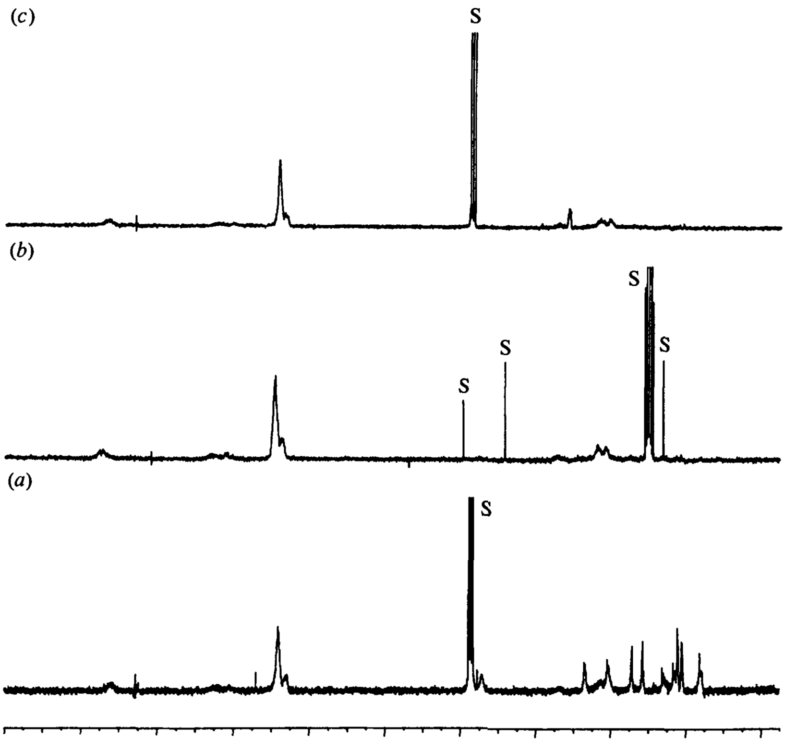


Fig. 2 ^{13}C NMR spectra of (*a*) styrene–dimenthyl fumarate copolymer **IVb iii** in $CDCl_3$; (*b*) copolymer **IVb iii** after hydrolytic cleavage of chiral auxiliary in [$^2H_6$]acetone; (*c*) fully methylated styrene–fumaric acid from hydrolysed **IVb iii** in $CDCl_3$ (S = solvent)

Table 3 Synthesis of copolymers **Va, b** derived from dec-1-ene and dialkyl fumarate, **IIIa, b**

Fumarate diester	Monomer feed; decene:**III**	Polymerisation[a] conditions *t*/h (*T*/°C)	Conversion[b] to copolymer (%)	Copolymer	Copolymer composition[f] decene:**III**	Copolymer $\bar{M}_w$[c]	[α]$^{25}_{D}$ (*c* 1, THF)[d,e]
IIIa	1:1[e]	14 (70)	28	**Va i**	—	7460	−39.1
IIIa	1:1[e]	20 (70)	33	**Va ii**	1:1	7715	−40.0
IIIa	1:1[e]	15 (70)	25	**Va iii**	9:10	8575	−38.7
IIIb	1:1[e]	36 (70)	20	**Vb i**	1:1	7210	−58.5
IIIb	1:1[e]	24 (70)	8	**Vb ii**	1:1	7135	−57.6
IIIb	1:1[e]	36 (70)	30	**Vb iii**	1:1	6285	−58.3
IIIb	1:1[e]	48 (65)	15	**Vb iv**	1:1	8035	−57.8
IIIb	1:1[e]	16 (70)	24	**Vb v**	1:1	7970	−59.1
IIIb	5:1	36 (60)	10	**Vb vi**	1:1	7305	−56.1
IIIb	5:1	72 (65)	17	**Vb vii**	1:1	6285	−55.6
IIIb	5:1	144 (60)	30	**Vb vii**	1:1	6945	−56.2

[a–d] See footnotes Table 1. [e] Different batches of **IIIa** and **IIIb** in each case. [f] From ^{1}H NMR spectra.

Table 4 Synthesis of copolymers **VIa, b** derived from isobutyl vinyl ether (IBVE) and dialkyl fumarate, **IIIa, b**

Fumarate diester	Monomer feed; IBVE:**III**	Polymerisation[a] conditions *t*/h (*T*/°C)	Conversion[b] to copolymer (%)	Copolymer	Copolymer composition[f] IBVE:**III**	Copolymer [α]$^{25}_{D}$ (*c* 1, THF)[d,e]
IIIa	1:1	16 (70)	32	**VIa i**	3:2	−39.9
IIIa	1:1	60 (60)	28	**VIa ii**	8:9	−40.1
IIIa	1:1	6 (60)	14	**VIa iii**	1:1	−39.6
IIIa	5:1	15 (70)	35	**VIa iv**	2:1	−38.9
IIIb	1:1	16 (80)	10	**VIb i**	1:1	65.6
IIIb	1:1	36 (80)	15	**VIb ii**	—	−66.6
IIIb	1:1	120 (80)	15	**VIb iii**	—	—
IIIb	1:1	108 (60)	24	**VIb iv**	1:1	—
IIIb	1:1	108 (55)	22	**VIb v**	5:4	−64.9
IIIb	1:1	336 (60)	26	**VIb vi**	1:1	—
IIIb	5:1	36 (80)	25	**VIb vii**	10:9	−63.4

[a–d] See footnotes Table 4.

Table 5 Optical rotations of homopolymers and copolymers of dialkyl fumarate monomers IIIa, b

Fumarate diester	Comonomer	Copolymer composition (comonomer:**III**)	[α]$^{25}_{D}$ (*c* 1, THF) Homopolymer of **IIIa** or **IIIb**	Copolymer
IIIa[a]	Styrene	**IVa** i–ix (~2:1)	−41.1	(−23 to − 30)
IIIb[c]	Styrene	**IVb** i–v (~2:1)	−58.2	(−39 to − 45)
IIIa	Dec-1-ene	**Va** i–iii (~1:1)	−41.1	(−38 to − 40)
IIIb	Dec-1-ene	**Vb** i–v (~1:1)	−58.2	(−56 to − 59)
IIIa	IBVE	**VIa** i–iv (~1:1)	−41.1	(−39 to − 40)
IIIb	IBVE	**VIb** i–vi (~1:1)	−58.2	(−63 to − 66)

[a] Concentration = 1 g/100 ml, THF, 25 °C. [b] [α]$^{25}_{D}$ monomer = −52.3. [c] [α]$^{25}_{D}$ monomer −96.3.

[α]$^{25}_{D}$ with content of **IIIb** is shown in Fig. 3. Although there is a fairly large uncertainty in the copolymer composition data it is quite clear that the [α]$^{25}_{D}$ composition relationship is not linear. As optically active comonomer segments are introduced [α]$^{25}_{D}$ rises sharply until a composition of *ca.* 33 mol% (65 mass%) is reached, and thereafter it levels quickly towards the value of the homopolymer of **IIIb**. If optically active segments do not influence each other and there are no main chain induction effects, [α]$^{25}_{D}$ might be expected to show a linear relationship with the mass% of chiral groups (since [α]$^{25}_{D}$ is measured at a concentration of 1 g/100 ml). This simple behaviour has been reported in the literature.[21] However, if the presence of one optically active sidechain substituent perturbs a neighbouring group, or if asymmetric induction of the copolymer main chain occurs, then considerable deviation from the simple linear relationship between [α]$^{25}_{D}$ and copolymer composition can occur.[11] Indeed, the structure of the non-optically active comonomer segment can also play a role as well.[21] Values of

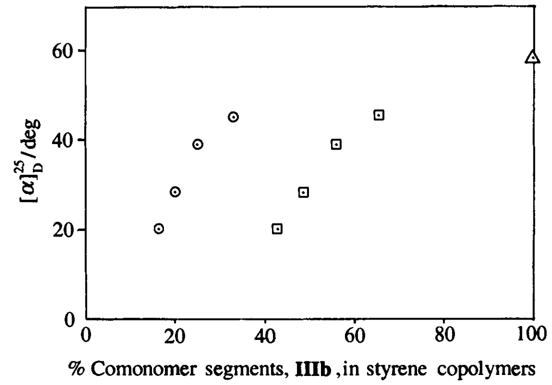


Fig. 3 Specific optical rotation, [α]$^{25}_{D}$, of copolymers of styrene with dimenthyl fumarate as a function of: (*a*) mol% of fumarate segments, ⊙; (*b*) mass% of fumarate segments, ▣ △ = datum for the homopolymer of dimenthyl fumarate

$[\alpha]_D^{25}$ which fall below the expected value based on the mass% of optically active monomer segments, have been used as an indicator of asymmetric induction in the main chain;[15] however, this conclusion requires many assumptions. In the final analysis optical activity of the main chain can only be shown by removal of all chiral auxiliaries. In the present work, it is interesting that all copolymers (and indeed the homopolymers of **IIIa** and **IIIb**) show $[\alpha]_D^{25}$ values below that expected based on the data for the two *monomers* (Table 5).

The complexity of the phenomena occurring is shown in our data where the $[\alpha]_D^{25}$ values of all copolymers, except one, are lower as expected, than that of the corresponding homopolymers. For copolymers of IBVE with **IIIb**, however, (*i.e.* **VIb** i–vi), the $[\alpha]_D^{25}$ values are consistently *higher* than that of the homopolymer of **IIIb**. While it is possible to speculate why this might arise, we have no evidence to underpin any of the possible reasons.

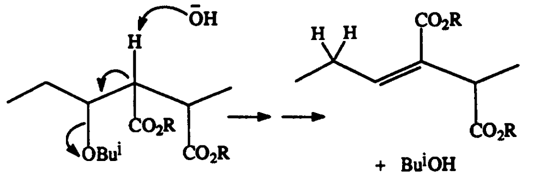
Removal of chiral auxiliaries by hydrolysis of fumarate copolymers

Most work was performed on the styrene copolymers. Routine hydrolysis procedures using aqueous alcoholic alkali,[19] and also acidic hydrolysis,[22] proved to be completely ineffective. A major factor seemed to be phase separation, and this led to experimentation with phase transfer catalysts. Eventually the satisfactory procedure reported in the Experimental section and employing 18-crown-6 and powdered KOH was evolved. Initially, the xylene solution of copolymer was clear, but as ester cleavage occurred, the solution gradually became opaque due to precipitation of the potassium salt of the fumaric acid copolymer. This eventually collected as a solid mass to leave the xylene solution clear again. Acidification of a cloudy aqueous solution of the copolymer salt yielded the white semi-crystalline styrene–fumaric copolymer, **VIII**, which is insoluble in $CHCl_3$ and hexane, but soluble in THF and methanol. The solubility of the copolymer in methanol is surprising, bearing in mind the content of styryl residues is 66%. This may arise because the copolymer adopts a micelle-like conformation, in which the styrene residues form the hydrophobic core, and the fumaric acid residues occupy the surface for hydrogen bonding with the methanol solvent. This may also explain the great difficulty experienced in trying to remove traces of solvent, notably THF, from the isolated hydrolysed copolymers, since these may be trapped within the hydrophobic pockets. This problem did not arise with any of the fumarate ester copolymers.

Complete hydrolysis of the copolymers and removal of the optically active fragments was established from the FTIR, ^1H and ^{13}C NMR spectra. In particular, the characteristic resonance of the α proton in the ester at *ca.* 4.5 ppm is no longer detectable and the large aliphatic proton signal from the menthyl groups is also absent (spectrum Fig. 1(*b*) for hydrolysed copolymer **IVb** iii, *Note*: the sharp resonances are due to trapped solvent as mentioned above). The corresponding ^{13}C NMR spectrum, Fig. 2(*b*), likewise is consistent with the loss of all menthyl groups. In the FTIR spectrum bands characteristic of the $-CO_2H$ group, at 3300 and 2800 cm^{-1} and a shift in the carbonyl frequency to 1710 cm^{-1} confirm hydrolysis is complete.

Hydrolysis of the dec-1-ene copolymers **V** was carried out using the optimised procedure developed with the styrene copolymers. The ^1H NMR spectra indicated qualitative removal of the chiral auxiliary, but the aliphatic proton region is complex in these species because of the dec-1-ene residues, and it is not possible to be definitive about complete removal of menthol and borneol groups. In addition, the hydrolysed products retained some solubility in chloroform (in contrast to the styrene–fumaric acid copolymers) possibly indicative of incomplete removal of chiral auxiliaries.

Hydrolysis of the IBVE copolymers using the optimised procedure resulted in clear pale yellow xylene solutions rapidly becoming dark red in colour. Attempts to isolate hydrolysed copolymers using procedures similar to those successfully applied to both the styrene and dec-1-ene analogues, failed to yield clean polymeric products, and clearly excessive degradation was being induced by the strongly basic conditions. Almost certainly elimination of isobutanol will be facile in these copolymers as a result of the acidic proton in the fumarate residues (Scheme 3). This would generate unsaturation in the polymer backbone (and hence a coloured product), and allow further reaction of the α,β-unsaturated ester and acid groups. Facile generation of colour in vinyl ether polymers is well known. As a result of this instability no attempt was made to characterise the products from these hydrolyses.



Scheme 3 Likely mechanism of initial base-induced degradation of IBVE-fumarate diester copolymers

Chiroptical properties of hydrolysed copolymers of styrene VII and dec-1-ene VIII with dibornyl IIIa and dimenthyl IIIb fumarates

The specific rotations, $[\alpha]_D^{25}$, of the styrene–fumaric acid copolymers, **VII**, and dec-1-ene–fumaric copolymers, **VIII**, obtained by hydrolysis of corresponding diborneyl and dimenthyl esters are shown in Table 6. Most work was performed with the styrene copolymers since these showed good evidence for quantitative removal of the chiral auxiliaries. In all cases the $[\alpha]_D^{25}$ values are low $+0.5$ to $+2.7$; most importantly, however, the values are all *positive* whereas the parent fumarate diester copolymers display strongly *negative* rotations. A number of different batches of diester **IIIa** (and also **IIIb**) were prepared and copolymerised by two of us, and the rotations of the hydrolysed copolymers are consistently positive. The spread in the measured values may, in part, arise from these multiple batches. These positive rotations are a clear indication of asymmetric induction in forming the stereogenic centres during the propagation reaction, and indeed the optically active main chain formed may account for the lower optical rotation of the diester copolymers (and the homopolymers) relative to that predicted from the content of optically active diester. We assume that induction occurs and overall optical activity is generated according to the *n*-ad (triad and higher) arguments put forward by Wulff.[3] Interestingly, Beredjick and Schuerch[23] as early as 1958 copolymerised *S*-α-methylbenzyl methacrylate with maleic anhydride, a 1,2-disubstituted alkene, to yield ester copolymers with negative optical rotations, analogous to the monomer. Hydrolysis of their copolymers yielded corresponding optically active acid copolymers with the opposite sign of rotation. The authors recognised that asymmetric induction must be occurring but it is not clear if they appreciated all the stereochemical requirements needed. Okamoto and Nakano, in their recent review[2] place this polymerisation into the category of 'cyclic olefin' copolymerisation where the initial cyclic structure of the olefin is crucial in the mechanism of induction. This is presumably the case as well with the more recent work reported by Dahl *et al.*[10,11] where a similar strategy to that of Beredjick and Schuerch[23] was adopted, in which the methacrylate ester was replaced by an optically active styrene, and the maleic anhydride by non-chiral cyclic maleimides. In our work though we have employed 1,2-disubstituted alkenes (fumarates) the monomers are not cyclic and only the *n*-ad mechanism of Wulff[3] seems applicable in generating asymmetry in the main chain.

Table 6 Optical rotations of copolymers following hydrolytic cleavage of chiral auxiliary

			$[\alpha]_D^{25}$ (*c* 1, THF)		
Fumarate diester	Comonomer	Copolymer	Copolymer	Hydrolysed copolymer	Methylated[a] copolymer
IIIa	Styrene	**IVa i**	−27.5	+0.5	+1.1
IIIa	Styrene	**ii**	−27.7	+1.8	−0.6
IIIa	Styrene	**iii**	−29.7	+2.7	—
IIIa	Styrene	**iv**	−23.6	+1.0	—
IIIa	Styrene	**v**	−27.2	+1.2	—
IIIa	Styrene	**ix**	−28.2	+0.5	+0.6
IIIb	Styrene	**IVb i**	−39.2	+1.0	—
IIIb	Styrene	**ii**	−45.1	+0.6	−1.8
IIIb	Styrene	**iii**	−44.1	+1.3	−2.5
IIIa	Dec-1-ene	**Va ii**	−40.0	−1.9	—
IIIa	Dec-1-ene	**iii**	−38.7	~0	~0
IIIb	Dec-1-ene	**Vb i**	−58.5	−8.1	—
IIIb	Dec-1-ene	**v**	−59.1	−2.3	~0

[a] Methylated version of hydrolysed copolymer.

Unfortunately, the amounts of homopolymers of **IIIa** and **IIIb** available to us were too small to allow us to pursue hydrolysis of these and determine whether the poly(fumaric acid)s formed were optically active. According to Wulff's reasoning[3] this would be possible if an excess of fumarate residues generated pairs of stereogenic centres of opposite absolute configuration and that these were spaced by other fumarate residues with a more random distribution of configuration of stereogenic centres. Wulff himself has reported formation of optically active homopolystyrene *via* copolymerisation of his bis-4-vinylphenyl boronate derivative of D-mannitol with styrene followed by stripping of all functionality from the styryl residues.[3] Kakuchi *et al.*[24] have also reported that the homopolymerisation of a divinyl monomer of a chiral template can form an optically active main chain following removal of the chiral template. However, the same group has reported[25] complete failure to produce optically active homopolymer from homopolymerisation of a divinyl monomer of another template and also from copolymers derived from this and a structurally appropriate non-chiral spacer monomer, following in each case removal of the chiral template. This shows just how complex these systems are, and how extrapolating from the results of polymerisations of one optically active system, to predict the outcome in other systems, is extremely difficult. More work and more data are required to produce a comprehensive understanding.

Further chemical modification of our optically active styrene–fumaric acid copolymers, **VII**, was demonstrated by reaction with excess diazomethane to generate the dimethyl ester analogue. Quantitative derivatisation was confirmed by the FTIR spectrum, but most convincingly by the ^{1}H and ^{13}C NMR spectra [Figs. 1(*c*) and 2(*c*) for the copolymer derived from **IVb** iii], where appropriate integration of the ^{1}H NMR resonances shows essentially complete esterification. Interestingly, the specific rotation, $[\alpha]_D^{25}$, of the methylated copolymers shows a small negative rotation for the species derived from copolymer **IVb** (i and iii), but the results from copolymer **IVa** (i, ii and **ix**) are less clear-cut.

The CD spectra of the styrene–fumaric acid copolymer **VII** and its fully methylated ester, each derived from the dimenthyl fumarate copolymer **IVb** iii, both displayed a weak positive band at 219 and 219.6 nm, respectively, compared to a sizeable positive band at 221 nm for the parent copolymer (Fig. 4). No Cotton effect was observed. These bands arise largely from the aromatic $\pi \longrightarrow \pi^*$ transitions implying an asymmetric environment around the styrene residues. It was not possible to conclude anything about the symmetry around the fumaric acid and ester residues.

The results from our hydrolysed dec-1-ene–fumarate copolymers **VIII** are less clear-cut than those from the stryrene–fumaric acid copolymers, **VIII**. The $[\alpha]_D^{25}$ values determined are all negative (Table 6) *i.e.* of the same sign as the parent ester copolymers. The NMR analysis suggests that hydrolysis may be incomplete with these copolymers, and, with the species derived from **Vb** i, $[\alpha]_D^{25} = -8.1$, this appears to be the case. There seems no reason why fully hydrolysed species **VIII** should not display positive rotations analogous to those of **VII**. However, predictions of this type are very difficult to make and it may well be that pure copolymers, **VIII**, may indeed display a negative rotation. More work is required to establish this.

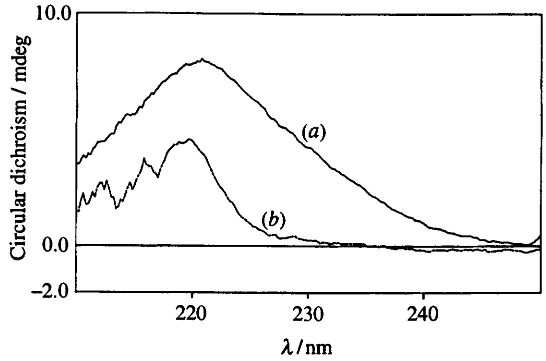


Fig. 4 Circular dichroism spectra of: (*a*) styrene–dimenthyl fumarate copolymer **IVb**; (*b*) same copolymer after cleavage of all chiral auxiliaries and quantitative methylation of the free carboxylic acid groups

Conclusions

Copolymers derived from styrene and optically active diesters of fumaric acid are readily prepared from widely available and relatively cheap starting materials. The procedures employed are also amenable to scale-up. Efficient hydrolysis of the copolymers is possible with the generation ~2:1 styrene–fumaric acid copolymers. The latter are also intrinsically optically active as a result of asymmetric induction during the propagation reaction. The source of optical activity is almost certainly the asymmetry arising from specific *n*-ad (triad and higher) placements in the backbone as predicted[3] and shown earlier[4] by Wulff. Complete methylation of the styrene–fumaric acid copolymers has been achieved demonstrating that these optically active polymers could form the basis for the cost-effective synthesis of novel opto- or optoelectronic-polymeric materials in the future, or indeed act as a novel source of chromatographic chiral stationary phases.

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