Homolytic Reactions of Ligated Boranes. Part 18.[1] The Scope of Enantioselective Hydrogen-atom Abstraction by Chiral Amine–Boryl Radicals for Kinetic Resolution under Conditions of Polarity Reversal Catalysis

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A variety of new and previously-known optically active amine–borane complexes have been used as polarity reversal catalysts for the kinetic resolution of representative racemic carbonyl-containing compounds. The key step involves enantioselective abstraction of hydrogen from a C–H bond α to the carbonyl function by optically active amine–boryl radicals derived from the catalyst by hydrogen-atom transfer to *tert*-butoxyl radicals generated by photolysis of di-*tert*-butyl peroxide. Chiral discrimination is generally not large, although enantioselectivity factors up to 8.8 were obtained at −74 °C in oxirane as solvent. The more reactive substrate enantiomer can generally be predicted by consideration of the steric interactions between the substituents attached to the boron atom and to the α-carbon atom in the diastereoisomeric transition states. However, hydrogen bonding and dipole–dipole interactions, together with stereoelectronic effects, may also play a part in determining enantioselectivity particularly when there is not marked steric asymmetry around the reacting centres.

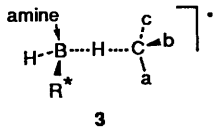
In Part 16 of this series[2] we described how the concept of polarity reversal catalysis (PRC)[3,4] of hydrogen-atom transfer reactions could be applied to the kinetic resolution of esters and of camphor. Electrophilic *tert*-butoxyl radicals abstract hydrogen relatively slowly from an electron-deficient α-C–H group in an ester, because of adverse polar effects in the transition state. However, this abstraction is catalysed by an amine–borane complex, through the cycle of reactions (1) and (2) which both

$$Bu^tO^{\bullet} + \text{amine}{\rightarrow}BH_2R \xrightarrow{\text{fast}} Bu^tOH + \underset{\mathbf{1}}{\text{amine}{\rightarrow}\dot{B}HR} \quad (1)$$

$$\text{amine}{\rightarrow}\dot{B}HR + \underset{\mathbf{2}}{HCR^1R_2CO_2R^3} \xrightarrow{\text{fast}} \text{amine}{\rightarrow}BH_2R + R^1R^2\dot{C}CO_2R^3 \quad (2)$$

benefit from favourable polar effects, because the B–H bond is electron rich and the amine–boryl radical **1** is highly nucleophilic.[3] If the amine–boryl radical and the ester **2** are chiral, then the α-hydrogen-transfer reaction (2) will be enantioselective and it may, in principle, be used to bring about kinetic resolution of the racemic ester.[2,5,6]

In our initial work,[2,5,6] the 2:1 complex of isopinocampheylborane ($IpcBH_2$) with *N*,*N*,*N*′,*N*′-tetramethylethylenediamine (TMEDA) was employed as the optically active polarity reversal catalyst, together with some closely related TMEDA–boranes. It was suggested that steric interactions between the groups attached to boron and those attached to the α-carbon atom of the substrate, in a transition state of the general structure **3**, could account for the chiral selectivities observed.[2]



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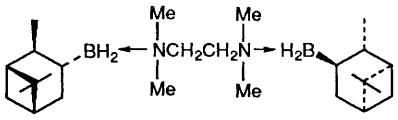
However, the enantioselectivities achieved were not large and it was noted that factors other than steric strain will probably also be important in determining the relative stabilities of the diastereoisomeric transition states. In the present paper we describe further studies of the enantioselective hydrogen-atom abstraction reactions of chiral amine–boryl radicals with a variety of substrates containing electron deficient C–H groups α to a carbonyl function, in an attempt to define more precisely the factors which influence chiral discrimination. As before,[2] di-*tert*-butyl peroxide (DTBP) was photolysed in the presence of the substrate and an optically active amine–borane complex which acts as a polarity reversal catalyst, as illustrated in reactions (1) and (2).

Results and Discussion

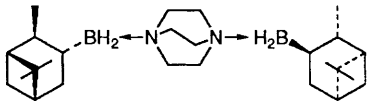
Amine–Boranes.—The chiral amine–borane complexes used are shown in structures **4**–**12**. The isopinocampheylborane complexes **4**–**6** with TMEDA,[2,7] 1,4-diazabicyclo[2.2.2]octane (DABCO)[8] and quinuclidine, respectively, are those derived from (1*R*)-(+)-α-pinene by hydroboration followed by reaction of Ipc_2BH with the appropriate amine; the enantiomeric forms obtained from (1*S*)-(−)-α-pinene were also examined. The superscript *d* or *l* is used with the acronyms shown to indicate whether the starting pinene (which was essentially optically pure) was dextro- or laevo-rotatory.[2]

(2*R*,5*R*)-(−)-2,5-Dimethylpyrrolidine was prepared according to the method of Short *et al.*[9] and its *N*-methyl derivative was prepared in a similar way by treatment of the bis(methanesulfonate) of (2*S*,5*S*)-(−)-hexane-2,5-diol with methylamine. These amines and (*S*)-(−)-2-hydroxymethyl-*N*-methylpyrrolidine,[10] each with an estimated enantiomeric excess (e.e.) of ⩾96%, were treated with borane–dimethyl sulfide (BMS) to yield the complexes **7**–**9**. The (*E*)-configuration shown for **9** is tentative and is based on nuclear Overhauser enhancement (NOE) difference spectroscopy (see Experimental Section).

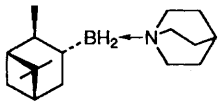
The polycyclic amine–boranes **10** and **11** show high thermal stability and are stable in air for long periods, presumably as a result of incorporating the N→B linkage into a six-membered ring. The N→B dative bond in **12** is evidently weakened by steric effects and this complex decomposed during attempted distillation with a bath temperature of *ca.* 150 °C and



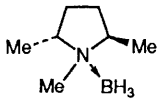
4; ^{d}IpcT



5; ^{d}IpcD



6; ^{d}IpcQ



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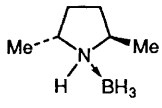

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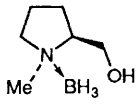

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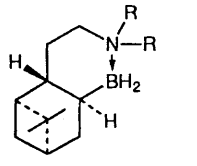
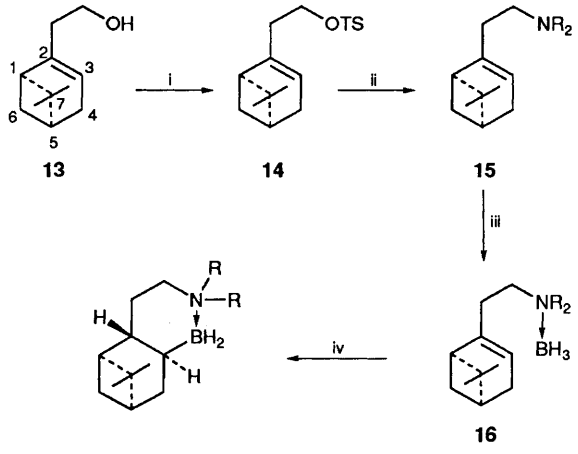


10 R_2N— = 

11 R_2N— = Et_2N—

12 R_2N— = $Bu^i{}_2N$—

underwent partial decomposition during chromatography on silica gel or during exposure to the atmosphere for 8 h. By contrast, **10** and **11** were readily distillable, stable on silica gel and showed no sign of change after exposure to the atmosphere for 2 days. The complexes **10**–**12** were synthesised starting from (1*R*)-(−)-nopol **13** (91% e.e.), as shown in Scheme 1.



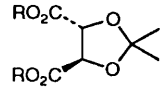
13 **14** **15** **16**

Scheme 1 *Reagents and conditions:* i, TsCl in pyridine, 0–5 °C; ii, R_2NH in THF, reflux; iii, BMS in diethyl ether, −20 °C; iv, reflux in toluene

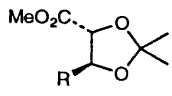
The ease with which the unsaturated amine–borane complex **16** undergoes cyclisation increases with the bulk of the *N*-alkyl groups along the series $R_2N = (CH_2)_4N < Et_2N < Bu^i{}_2N$, which suggests that thermally-induced cleavage of the N→B bond in **16** preceeds *syn*-hydroboration by free BH_3 at the less-hindered face of the double bond. The structures of the amine–boranes **6** and **10** have been determined by X-ray crystallography and will be reported separately.[11]

Substrates and Kinetic Resolutions.—The substrates **17**–**28** were examined and, for all of these compounds, amine–boryl radicals are expected to abstract hydrogen rapidly from a C–H group α to a carbonyl function.[2,3,5,6]

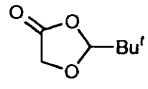
An oxirane solution containing racemic substrate, amine–borane catalyst, DTBP and an unreactive internal concentration standard was irradiated through quartz with unfiltered light from a 160 W medium-pressure mercury discharge lamp, as described previously.[2] The sample was immersed in a solid CO_2–ethanol bath and its internal temperature during photolysis was estimated to be *ca.* −74 °C.[2] Substrate consumption was determined by GLC (*tert*-butylbenzene reference) or ^{1}H NMR spectroscopy (1,4-di-*tert*-butylbenzene reference). The remaining substrate was recovered by column chromatography on silica gel and its e.e. was determined by ^{1}H NMR spectroscopy using a chiral shift reagent, by chiral stationary phase HPLC or by measurement of its optical rotation. Assignments were made by comparison with authentic substrates of known absolute configuration.



17 R = Me
18 R = Pr^i



19 R = Me
20 R = CH_2OH



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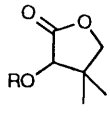
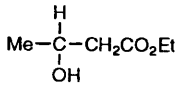


22 R = Me
23 R = Me_3Si



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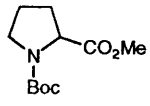

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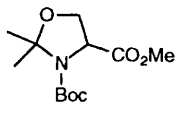

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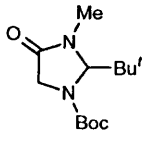

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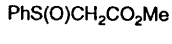

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If none of the α-carbonylalkyl radicals produced in reaction (2) go on to abstract hydrogen unselectively and thus regenerate racemic substrate, the enantioselectivity factor *s* will be given by eqn. (3).[12,13] Here k_A and k_B are the rate constants for

$$s = (k_A/k_B) \doteq \ln[(1 - C)(1 - EE)]/\ln[1 - C)(1 + EE)] \quad (3)$$

abstraction of hydrogen from the faster- and the slower-reacting enantiomer, respectively, *C* is the fraction of substrate consumed and *EE* is the fractional e.e. of the substrate which remains. It appears probable[2] that some of the α-carbonylalkyl radicals will decay by hydrogen-atom abstraction, probably mainly radical–radical disproportionation reactions, and thus application of eqn. (3) will give a lower limit for *s*. Results of

Table 1 Representative kinetic resolutions of racemic substrates using ^{d}IpcT **4** catalyst[a] in oxirane at −74 °C

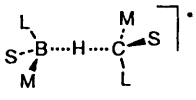
Substrate	UV irradn. time (min)	Substrate consumption (%)[b]	More reactive enantiomer	E.e. of residual substrate (%)[c]	Method for determination of e.e.[d]	Enantioselectivity factor s[e]	Steric chirality of more reactive enantiomer[f]
17	50	52 (A)	*S,S*	62 (*R,R*)	A	6.8[g]	ρ
18	30	55 (B)	*S,S*	74 (*R,R*)	A	8.8	ρ
19	65	21 (A)	4*S*,5*R*	8 (4*R*,5*S*)	A	2.0	ρ
20	180	45 (A)	4*S*,5*R*	44 (4*R*,5*S*)	A	5.1	ρ
21	45	44 (A)	*h*	8[i]	B	1.3	
22	180	42 (A)	*R*	8 (*S*)	A	1.3	(ρ)
23	110	31 (A)	*R*	15 (*S*)	A	2.3[j]	ρ
24	160	27 (A)	*S*	3 (*R*)	A	1.2	
25	120	20 (A)	*R*	10 (*S*)	C	2.6	(σ)
26	120	44 (B)	*S*	22 (*R*)	A	2.2	(ρ)
27	180	37 (B)	*S*	24 (*R*)	D[k]	3.0	ρ
28	105	57 (A)	*R*	8 (*S*)	B,D,E	1.2	

[a] Catalyst concentration 0.20 mol dm^{-3}. [b] Method for determination given in parentheses. A = GLC. B = ^{1}H NMR spectroscopy using 1,4-di-*tert*-butylbenzene as reference. [c] Enantiomer present in excess shown in parentheses. [d] A = ^{1}H NMR spectroscopy in the presence of [Eu(hfc)$_3$]. B = HPLC using Chiralcel OD stationary phase. C = ^{1}H NMR spectroscopy in the presence of [Eu(tfc)$_3$]. D = Optical rotation. E = ^{1}H NMR spectroscopy in the presence of (*S*)-(+)-DNPB. [e] Calculated using eqn. (3). [f] See text. Assignments in parentheses are very tentative. [g] With ^{d}IpcT catalyst s = 7.4; the (*R,R*)-enantiomer is the more reactive. [h] Enantiomer eluting first. [i] Enantiomer eluting second. [j] With ^{d}IpcT catalyst s = 2.1; the (*S*)-enantiomer is the more reactive. [k] The residual substrate showed $[\alpha]_D^{22}$ +3.55 (*c* 2.05, CH_2Cl_2).

kinetic resolutions using ^{d}IpcT **4** as catalyst are presented in Table 1.

If a kinetic resolution is to yield useful quantities of material with a high e.e., the value of s must be $\geqslant 5$.[12,13] Apart from the results obtained for the structurally-related substrates **17**, **18** and **20**, the values of s in Table 1 are rather small. Although these enantioselectivities would undoubtedly increase at lower temperatures,[2] the latter are not readily accessible using standard laboratory equipment for photochemical reactions.

We have suggested that if long-range torsional/steric interactions (front strain) between the substituents on the boron and carbon atoms are dominant in determining the preferred geometry of the transition state, then this should be of the type **29**, in which the symbols L, M, and S refer to groups of large,



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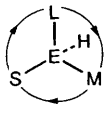
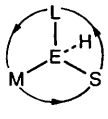
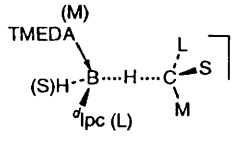
medium and small effective bulk.[2] In this transition state a boron-centre of steric chirality[2] ρ is associated with a carbon-centre of steric chirality σ (see structures **30a** and **30b**, E = B or C). Conversely, a boron-centre of steric chirality σ will give a lower energy transition state when associated with a carbon-centre of steric chirality ρ than with one of steric chirality σ. We have noted[2] that the preferred configuration at the boron-centre in a transition state for hydrogen abstraction by the amine–boryl radical derived from ^{d}IpcT is probably σ and thus the more reactive enantiomer of a substrate should have steric chirality ρ, as shown in **31**. The steric chiralities of the more reactive (*S,S*)-enantiomers of the isopropylidene tartrates[14] **17** and **18** can be predicted with the aid of molecular models and indeed appear to be ρ, as required if steric strain effects are dominant. The same steric chirality ρ is associated with the (4*S*,5*R*)-enantiomers of **19** and **20**; the lower value of s for **19** is probably a consequence of the decreased bulk of the large substituent [–CH(Me)OR] in this substrate.



30a (ρ)



30b (σ)



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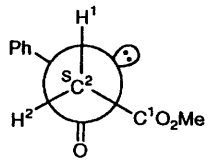
It is often not easy to deduce the effective helicity of the steric environment around the reactive α-C–H bond in a substrate and the energy differences between the diastereoisomeric transition states are certainly very small for all the substrates **17**–**28**. However, it does appear that the steric chiralities of the more reactive enantiomers of **22**, **23**, **26** and **27** are also ρ.* For **27** (and for **21**) it is assumed that the hydrogen atom which is abstracted preferentially is that *trans* to the bulkyl *tert*-butyl group. Increasing the size of the substituent at the α-carbon from MeO in **22** to Me_3SiO in **23** leads to an appreciable increase in s, which can be ascribed to the increase in steric asymmetry caused by increasing the difference in bulk between the small-[–C(=O)OCH_2] and medium-sized (–OR) substituents.

By inspection of molecular models, it is very difficult to decide on the steric chirality around the α-C–H bond in **25**. Taking the effective sizes of the groups attached to C_α in the transition state to decrease in the order Boc(R)N > RCH_2 > MeO_2C for both amide rotamers, which appears to be marginally the most likely alternative, then the (*S*)-enantiomer has steric chirality ρ. However, it is the (*R*)-enantiomer which is the more reactive when ^{d}IpcT is the catalyst. The relative importance of steric interactions between groups near to the reaction centre compared with those between groups more distant from it could vary with the structure of the abstracting amine–boryl radical for such finely balanced systems and a simplistic model based on transferable steric chiralities of the reactants is quite likely to prove inadequate.

The preferred conformation about the α-C–S in the sulfoxide **28** would be predicted on steric grounds to be that depicted in

* This tentative assignment applies to both amide rotamers of each of the substrates **26** and **27**.



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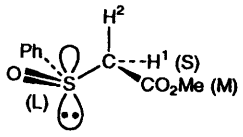

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32 for the (*R*)-enantiomer. The conformation adopted by **28** in the solid state was shown by X-ray crystallography to be close to the idealised structure **32**, with the dihedral angles C^1–C^2–S=O and C^1–C^2–S–C_{Ar} equal to 65.1 and 174.2°, respectively.[15] If we assume that this conformation is maintained in the transition state for α-hydrogen-atom abstraction in solution then, provided steric effects dominate, the less hindered H^1 should be transferred preferentially to boron and the steric chirality of the (*R*)-enantiomer would be σ. However, if stereoelectronic effects are dominant,* the more reactive α-C–H bond could be that antiperiplanar to the sulfur lone pair front-lobe (maximum back-lobe interaction)[16] and H^2 will then be transferred preferentially. Now the steric chirality of the (*R*)-enantiomer is ρ (see structure **33**) and this enantiomer would be predicted to react more rapidly with the amine–boryl radical derived from ^{d}IpcT, as observed.

The efficiencies of **4**–**12** as catalysts for kinetic resolutions of **17**, **18** and **23** were compared and the results are presented in Table 2. With the exception of **9**, all catalysts showed appreciably greater values of *s* with the isopropyl ester **18** than with the less sterically demanding methyl ester **17**. The most encouraging results were obtained from ^{d}IpcT **4** and the polycyclic amine–boranes **10** and **11**, which gave the highest enantioselectivities and were readily prepared and handled (^{d}IpcT and IpcT are commercially available; **10** and **11** exhibit high thermal- and air-stability). In a preparative run starting with 3 mmol of racemic substrate **23** and using **11** as catalyst, (*S*)-*O*-trimethylsilylpantolactone having an e.e. of 84% was isolated after 71% substrate consumption (*s* = 4.9).

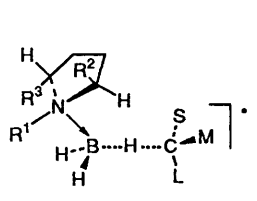
Molecular models indicate that the steric asymmetry around boron is somewhat smaller for IpcD or IpcQ than for IpcT, in accord with the greater enantioselectivities found with the latter as catalyst. It is also possible that the unreacted $IpcBH_2$ group could interact in the transition state for hydrogen-atom abstraction by the amine-boryl radical derived from IpcT† to increase enantioselectivity in a way not possible when the two boron moieties are rigidly held apart in IpcD. The enantioselectivity realised with the quinuclidine complex ^{d}IpcQ 6, which contains only one $IpcBH_2$ group, is similar to that obtained with ^{d}IpcD **5**.

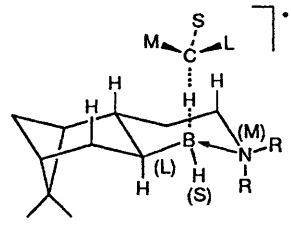
The secondary amine–borane **8** contains an NH group and was included to ascertain whether hydrogen bonding between the NH and C=O groups in the transition state would increase enantioselectivity.‡ However, substrate conversions using **8** were low, samples rapidly developed a yellow colour during photolysis and enantioselectivities were similar to those achieved with **7**. We have shown previously[18,19] that secondary amine–boryl radicals readily abstract hydrogen from their parent amine–boranes to form electrophilic aminyl-borane radicals [reaction (4)] which do not abstract hydrogen from

$$R_2NH{\rightarrow}\dot{B}H_2 + R_2NH{\rightarrow}BH_3 \longrightarrow R_2NH{\rightarrow}BH_3 + R_2\dot{N}{\rightarrow}BH_3 \quad (4)$$

C–H groups α to carbonyl functions. Although the substrates investigated in this work are all highly reactive towards amine–boryl radicals, some contributions from reaction (4) seems the likely cause of the problems encountered with **8**.

Examination of molecular models indicates that the steric chiralities of the amine–borane residues in the transition states for reactions mediated by **5**–**12** are all σ, as for reactions involving ^{d}IpcT. Hence, if steric effects are dominant the more reactive enantiomer of all substrates should be ρ (see Table 1), as observed. For **7**-**9** this prediction is based on the preferred transition state geometry shown in **34**. For **10**–**12**, the argument assumes that the hydrogen atom which is transferred will occupy a position in the transition state similar to that of the more exposed axial hydrogen attached to boron in the parent amine–boranes (see structure **35**).





34a $R^1 = R^2 = R^3 = Me$
34b $R^1 = H$, $R^2 = R^3 = Me$
34c $R^1 = Me$, $R^2 = H$, $R^3 = CH_2OH$

35

The amine–borane **9** was examined in the hope that the pendant CH_2OH group might be involved in hydrogen bonding with the substrate in the transition state **34c**, leading to enhanced enantioselectivity. However, no such increases are

Table 2 Enantioselectivity factors *s*[a] obtained from kinetic resolutions of **17**, **18** or **23** using different amine–borane catalysts in oxirane at −74 °C

	s		
	Substrate[a]		
Catalyst[b]	**17**	**18**	**23**
^{d}IpcT **4**[c]	6.7 (*S*,*S*)	8.8 (*S*,*S*)	2 3 (*R*)
^{d}IpcD **5**[c]	3.0 (*S*,*S*)	—	—
^{d}IpcQ **6**	3.2 (*S*,*S*)	—	—
7	1.4 (*S*,*S*)	2.1 (*S*,*S*)	1.9 (*R*)
8	1.3 (*S*,*S*)	3.4 (*S*,*S*)	—
9	2.0 (*S*,*S*)	2.0 (*S*,*S*)	1.4 (*R*)
10	1.8 (*S*,*S*)	—	1.7 (*R*)
11	2.1 (*S*,*S*)	7.6 (*S*,*S*)	5.2[d] (*R*)
12	1.9 (*S*,*S*)	5.6 (*S*,*S*)	—

[a] The more reactive enantiomer is given in parentheses; in every case its steric chirality is ρ. [b] Catalyst concentration 0.40 mol dm^{-3}, except where stated otherwise. [c] Catalyst concentration 0.20 mol dm^{-3}. [d] When the catalyst concentration was doubled to 0.80 mol dm^{-3}, *s* = 5.9.

* This could happen because of a captodative interaction between the sulfur lone pair and the carbonyl group, with the latter orientated for maximum π-overlap with the developing singly-occupied orbital on C_α in the transition state.

† The structure of ^{d}IpcT has been determined by X-ray crystallography.[17]

‡ Molecular orbital calculations predict that such interactions can be important.[11]

evident from the results summarised in Table 3. The direction of the small enantioselectivities observed can be rationalised in terms of the steric strain model. Now, in accord with this model, the (*S*)-enantiomer of **25** is more reactive than its antipode, in contrast with the result obtained when ^{d}IpcT was used as catalyst (see Table 1).

Improvements in enantioselectivity as a result of possible interactions between an OH group in the substrate and the polar N→B linkage were sought in kinetic resolutions of **20** (see Table 4). The (4*S*,5*R*)-enantiomer is the more reactive with all catalysts, in accord with the steric strain model. When the catalyst is **4**, **7** or **9**, the enantioselectivities achieved with **20** are close to those obtained with the similarly-shaped aprotic **17** (see Table 2). However, with **10** and **11** the values of *s* for resolution of **20** were appreciably greater than those obtained with **17**, suggesting that dipolar interactions may be important for these catalysts.

Conclusions.—The enantioselectivities achieved so far for hydrogen-atom abstraction by chiral amine–boryl radicals are not large. The more reactive substrate enantiomer can generally be predicted by consideration of the steric interactions between the substituents attached to the boron atom and to the α-carbon atom in the diastereoisomeric transition states of the general type **3**. However, hydrogen bonding and dipole–dipole interactions, together with stereoelectronic effects, may also play a part in determining enantioselectivity particularly when there is not marked steric asymmetry around the reacting centres. Larger enantioselectivities might be obtained with amine–boranes in which there is a relatively rigid and more sterically asymmetric environment around the boron atom.[20]

Experimental

NMR spectra were recorded using a Varian VXR-400 instrument (400 MHz for ^{1}H). The solvent was $CDCl_3$ and chemical shifts are reported relative to Me_4Si (^{1}H and ^{13}C) and to external $Et_2O{\cdot}BF_3$ (^{11}B); *J* values are quoted in Hz. The optically active shift reagents [Eu(hfc)$_3$] and [Eu(tfc)$_3$] (Aldrich) and DNPB (Fluka) were used as supplied.* Mass spectra were obtained using VG 7070H or VG ZAB-2F instruments. GLC analyses were carried out using a Pye-Unicam 204 chromatograph equipped with flame-ionisation detector and a Hewlett-Packard model 3392A integrator. A glass column (2 m × 4 mm) packed with 10% OV-101 on Chromosorb WHP 80-100 mesh was used with nitrogen carrier gas. HPLC was carried out using a Gilson 305 instrument in conjunction with UV or refractive index detectors; a 250 mm × 4 mm column containing Chiralcel OD (Daicel Chemical Industries) was used to effect analytical separation of enantiomers (hexane–isopropyl alcohol mobile phase). Column chromatography and TLC were carried out using Merck Kieselgel 60 (230–400 mesh) and Kieselgel 60 F_{254} aluminium-backed pre-coated plates, respectively. Optical rotations were determined at 589 nm (sodium D line) with an Optical Activity AA-10 automatic digital polarimeter, using a 1 dm pathlength cell, and are given in units of 10^{-1} deg cm^2 g^{-1}.

Materials.—All preparations and handling of boron-containing compounds were carried out under an atmosphere of dry argon. All solvents were dried by conventional methods and were stored under argon. (1*R*)-(+)- and (1*S*)-(−)-α-pinenes (Aldrich) were distilled from CaH_2; they showed $[\alpha]_D^{20}$ +51.1 and −51.1 (neat), respectively, corresponding[21] to an e.e. of >99%. Nopol **13** (Aldrich) was distilled before use and showed $[\alpha]_D^{20}$ −36.4 (neat) corresponding[22] to an e.e. of 91%. *tert*-Butylbenzene and TMEDA were distilled from CaH_2 and 1,4-di-*tert*-butylbenzene was recrystallised from diethyl ether. Di-*tert*-butyl peroxide (98%, Aldrich) was passed down a column of basic alumina (activity 1) and then distilled (b.p. 46–47 °C/76 Torr).† Quinuclidine, DABCO and BMS (10 mol dm^{-3} solution in excess Me_2S) (all Aldrich) and oxirane (Fluka) were used as received.

* The shift reagents used were tris[3-heptafluoropropylhydroxymethylene)-(+)-camphorato]europium(III) [Eu(hfc)$_3$], tris[3-(trifluoromethylhydroxymethylene)-(+)-camphorato(III) [Eu(tfc)$_3$] and (*S*)-(+)-3,5-dinitro-*N*-(1-phenylethyl) benzamide (DNBP).

Table 3 Enantioselectivity factors *s* obtained from kinetic resolutions using **9** as catalyst[b] in oxirane at −74 °C

Substrate	*s*[a]
17	2.0 (*S*,*S*)
18	2.2 (*S*,*S*)
19	1.7 (4*S*,5*R*)
20	1.6 (4*S*,5*R*)
21	1.2[c]
22	1.7 (*R*)
23	1.4 (*R*)
25	2.2 (*S*)
26	2.1 (*S*)

[a] The more reactive enantiomer is given in parentheses. [b] Catalyst concentration 0.40 mol dm^{-3}. [c] Enantiomer eluting first during HPLC analysis using Chiralcel OD stationary phase.

Table 4 Enantioselectivity factors *s* obtained from kinetic resolutions of **20** using selected catalysts[b] in oxirane at −74 °C

Catalyst[b]	*s*[a]
4[c]	5.1 (4*S*,5*R*)
7	2.2 (4*S*,5*R*)
9	1.6 (4*S*,5*R*)
10	4.6 (4*S*,5*R*)
11	3.2 (4*S*,5*R*)

[a] The more reactive enantiomer is given in parentheses; its steric chirality appears to be p. [b] Catalyst concentration 0.40 mol dm^{-3} except where stated otherwise. [c] Catalyst concentration 0.20 mol dm^{-3}.

Amine–Borane Catalysts.—The amine–boranes ^{d}IpcT **4**[2,7] (m.p. 120–145 °C decomp., lit.,[7] m.p. 140–141 °C) and ^{d}IpcD **5**[8] (m.p. 124–147 °C decomp., lit.,[8] m.p. 160–161 °C) were prepared as described in the literature. The complexes ^{l}IpcT and ^{l}IpcD were prepared from (1*S*)-(−)-α-pinene in the same way as their antipodes.

The quinuclidine complex ^{d}IpcQ **6** and its antipode were prepared in a similar way to ^{d}IpcT by treatment of $^{d}Ipc_2BH$ with 1 mol equiv. of quinuclidine. Recrystallisation from diethyl ether–hexane (6:4 v/v) gave ^{d}IpcQ, m.p. 74–76 °C (Found: C, 78.1; H, 12.6; N, 5.2. $C_{17}H_{32}BN$ requires C, 78.2; H, 12.4; N, 5.4%); δ_H 0.63 (m, 1 H), 0.76 (d, 1 H, *J* 8.71), 0.94 (d, 3 H, *J* 7.05), 1.07 (s, 3 H), 1.12 (s, 3 H), 1.52 (m, 2 H), 1.72 (m, 7 H), 1.77 (m, 2 H), 1.98 (m, 2 H), 2.16 (m, 2 H) and 2.98 (m, 6 H); δ_C 20.67, 22.44, 22.84, 25.01, 28.45, 34.13 (2 peaks), 38.33, 38.95, 42.62, 43.08, 48.61 and 51.83; δ_B 1.46 (br s).

The Pyrrolidines.—(2R,5R)-(−)-2,5-*Dimethylpyrrolidine.* This was prepared as described by Short *et al.*,[9] b.p. 102 °C (lit.,[9] b.p. 102–103 °C); $[\alpha]_D^{22}$ −7.1 (*c* 10.0, MeOH). The hydrochloride, m.p. 201–204 °C, showed $[\alpha]_D^{22}$ +5.58 (*c* 3.5, CH_2Cl_2) (lit.,[9] m.p. 200–203 °C, $[\alpha]_D^{24}$ +5.57), indicating[9] that the e.e. of the free amine is 96–98%.

(2R,5R)-(−)-N,2,5-*Trimethylpyrrolidine.* Methylamine (8.0

† 1 Torr = 133.32 Pa.

g, 0.26 mol) was condensed onto the bis(methanesulfonate) of (2*S*,5*S*)-hexane-2,5-diol[9] (14.0 g, 0.051 mol) contained in a thick-walled flask. The flask was closed with a greaseless stopcock and the mixture was shaken with cooling (below −10 °C) until a homogenous solution was obtained. The solution was allowed to warm to room temperature and left to stand for 10 h with occasional shaking. The published procedure[9] for work-up of 2,5-dimethylpyrrolidine was followed to yield the amine (5.3 g, 81%), b.p. 120–123 °C; $[\alpha]_D^{20}$ −75.6 (*c* 5.3, MeOH). Since the bis(methanesulfonate) was from the same batch as was used to prepared 2,5-dimethylpyrrolidine, the e.e. of the *N*-methylated amine is also estimated to be 96–98%. δ_H 0.94 (d, 6 H, *J* 6.30), 1.42 (m, 2 H), 1.97 (m, 2 H), 2.26 (s, 3 H, *N*-Me) and 2.91 (m, 2 H); δ_C 16.58, 31.08, 34.79 and 57.43 (Found: M^+, 113.1210. $C_7H_{15}N$ requires *M*, 113.1209).

(S)-(−)-2-*Hydroxymethyl*-N-*methylpyrrolidine*. This was prepared from (*S*)-(−)-proline by the published method,[10] b.p. 45 °C/0.5 Torr (lit.,[10] b.p. 71–74 °C/21 Torr); $[\alpha]_D^{22}$ −7.2 (*c* 5.0, $CHCl_3$), −59.0 (*c* 3.9, MeOH) {lit.,[10] $[\alpha]_D^{25}$ −5.036 (*c* 0.1, neat}; δ_H 1.70 (m, 4 H), 2.25 (m, 2 H), 2.30 (s, 3 H, *N*-Me), 2.92 (br s, 1 H, OH), 3.05 (m, 1 H), 3.39 (m, 1 H) and 3.60 (m, 1 H); δ_C 23.18, 27.50, 40.53, 57.50, 61.60 and 66.05.

The Pyrrolidine–Boranes.—(2R,5R)-N,2,5-*Trimethylpyrrolidine–Borane* **7**. BMS (2.00 cm^3, 20 mmol) in diethyl ether (5 cm^3) was added dropwise to a stirred solution of the *N*,2,5-trimethylpyrrolidine (2.30 g, 20 mmol) in diethyl ether (10 cm^3) cooled in an ice–water bath. After the addition, the mixture was stirred for 30 min, allowed to warm to room temperature and then stirred for a further 1 h. The solvent and Me_2S were removed by evaporation under reduced pressure and the residual oil was distilled to give the title complex **7** (1.95 g, 77%), b.p. 73–75 °C/0.5 Torr; $[\alpha]_D^{20}$ −107.0 (*c* 5.4, $CHCl_3$); δ_H 1.16 (d, 3 H, *J* 6.93), 1.29 (d, 3 H, *J* 6.71), 1.44 (m, 1 H), 1.50 (br q, 3 H, J_{BH} 97, BH_3), 1.72 (m, 1 H), 1.99 (m, 1 H), 2.20 (m, 1 H), 3.01 (m, 1 H) and 3.51 (m, 1 H); δ_C 15.92, 16.54, 29.30, 29.54, 44.63, 65.64 and 66.21; δ_B −14.7 (q, J_{BH} 97) (Found: $M^+ - H$ 126.1459. $C_{17}H_{18}BN$ requires *M*-H, 126.1450).

(2R,5R)-2,5-*Dimethylpyrrolidine–Borane* **8**. This was prepared in a similar way to the complex **7**. The crude product was recrystallised from pentane at −10 °C to give the title complex, m.p. 42 °C; $[\alpha]_D^{20}$ −56.0 (*c* 3.1, MeOH); δ_H 1.23 (dd, 3 H, *J* 6.86 and 1.31), 1.33 (d, 3 H, *J* 6.52), 1.37 (br q, 3 H, J_{BH} 94, BH_3), 1.45 (m, 1 H), 1.65 (m, 1 H), 1.95 (m, 1 H), 2.17 (m, 1 H), 3.13 (m, 1 H), 3.49 (m, 1 H) and 3.72 (br s, 1 H, NH); δ_C 15.73, 19.43, 31.04, 31.67, 59.45 and 60.12; δ_B −20.2 (q, J_{BH} 94) (Found: C, 63.5; H, 14.0; N, 12.2. $C_6H_{16}BN$ requires C, 63.8; H, 14.3; N, 12.4%).

(S)-2-*Hydroxymethyl*-N-*methylpyrrolidine–Borane* **9**. BMS (1.70 cm^3, 17 mmol) in diethyl ether (5 cm^3) was added dropwise to a stirred solution of the 2-hydroxymethyl-*N*-methylpyrrolidine (2.00 g, 17.4 mmol) in diethyl ether (10 cm^3) cooled in a bath at *ca.* −40 °C. After the addition, the mixture was stirred at −40 °C for 15 min and then allowed to warm to room temperature. The solvent and Me_2S were removed by evaporation under reduced pressure and the residual solid was recrystallised from hexane–diethyl ether to give the title complex, m.p. 55–57 °C; $[\alpha]_D^{22}$ −9.6 (*c* 3.8, $CHCl_3$); δ_H 1.80–2.20 (m, 4 H), 1.50 (br q, 3 H, J_{BH} 97, BH_3), 2.70 (s, 3 H, *N*-Me), 2.75–2.95 (m, 3 H), 3.30 (m, 1 H) and 3.86 (m, 2 H); δ_C 20.71, 24.74, 52.50, 60.68, 65.38 and 72.69; δ_B −14.9 (q, J_{BH} 97) (Found: C, 55.7; H, 12.5; N, 10.7. $C_{16}H_{16}BNO$ requires C, 55.9; H, 12.5; N, 10.9%). A much larger NOE was observed for the *N*-methyl protons (δ 2.70) when 2-H (δ 3.30) was irradiated than when the methylene protons of the CH_2OH group (δ 3.86) were irradiated. However, when the *N*-methyl protons were irradiated, a much larger NOE was observed for 2-H than for the methylene protons of the CH_2OH group. This indicates that the *N*-methyl group and the CH_2OH group are probably on opposite sides of the ring in the single isomer obtained, which thus has the (*E*)-configuration.

The Nopylamines **15**.—Nopyl toluene-*p*-sulfonate[23,24] **14** was prepared from (1*R*)-(−)-nopol (91% e.e.) according to the published method.[23] The crude toluene-*p*-sulfonate, which was essentially pure by NMR spectroscopy, showed $[\alpha]_D^{22}$ −26.2 (*c* 7.5, $CHCl_3$) and, since no enantiomeric fractionation should have taken place prior to the measurement, the e.e. of this material will be 91%. Recrystallisation from pentane gave analytically pure toluene-*p*-sulfonate, m.p. 51–52 °C (lit.,[24a] m.p. 51.0–51.8 °C); $[\alpha]_D^{22}$ −26.9 (*c* 6.2, $CHCl_3$) and we assume the e.e. to be still 91%. This toluene-*p*-sulfonate (0.1 mol) and the appropriate amine (0.4 mol) in tetrahydrofuran (THF, 150 cm^3) were heated under reflux for 14 h (pyrrolidine and diethylamine) or for 48 h (diisobutylamine). After work-up as described for similar compounds[25] the nopylamines were purified by distillation; each is assumed to contain a 91% excess of the (1*R*)-enantiomer.

(1R)-N-*Nopylpyrrolidine*. Yield 95%, b.p. 70–72 °C/0.05 Torr (lit.,[23] b.p. 82–83 °C/0.3 Torr); $[\alpha]_D^{23}$ −34.0 (*c* 5.8, $CHCl_3$); δ_H 0.79 (s, 3 H), 1.11 (d, 1 H, *J* 8.0), 1.24 (s, 3 H), 1.76 (m, 4 H), 2.01 (m, 2 H), 2.17 (m, 4 H), 2.32 (m, 1 H), 2.43 (m, 2 H), 2.50 (m, 4 H) and 5.2 (s, 1 H); δ_C 21.22, 23.41, 26.31, 31.29, 31.66, 36.56, 37.98, 40.76, 45.99, 54.15, 54.66, 116.82 and 146.60.

(1R)-N-*Nopyl*-N,N-*diethylamine*. Yield 91%, b.p. 68–70 °C/0.05 Torr; $[\alpha]_D^{22}$ −32.6 (*c* 6.5, $CHCl_3$); δ_H 0.80 (s, 3 H), 1.00 (t, 6 H, *J* 7.15), 1.12 (d, 1 H, *J* 8.58), 1.24 (s, 3 H), 1.95–2.45 (complex, 8 H), 2.46 (m, 6 H) and 5.19 (m, 1 H); δ_C 11.87, 21.24, 26.33, 31.30, 31.68, 34.04, 37.97, 40.78, 46.08, 51.00, 116.70 and 146.79 (Found: C, 81.2; H, 12.1; N, 6.4. $C_{15}H_{27}N$ requires C, 81.4; H, 12.3; N, 6.3%).

(1R)-N-*Nopyl*-N,N-*diisobutylamine*. Yield 20%, b.p. 90–93 °C/0.05 Torr; $[\alpha]_D^{22}$ −21.8 (*c* 5.8, $CHCl_3$); δ_H 0.80 (s, 3 H), 0.85 (d, 12 H, *J* 6.68), 1.12 (d, 1 H, *J* 8.45), 1.25 (s, 3 H), 1.65 (m, 2 H), 1.90–2.45 (complex, 13 H) and 5.18 (m, 1 H); δ_C 20.92 (2*Me*$_2$CH), 21.23, 26.35, 26.65, 31.30, 31.67, 34.25, 37.95, 40.80, 46.08, 53.29, 63.69, 116.45 and 147.01 (Found; C, 82.4; H, 12.5; N, 4.9. $C_{19}H_{35}N$ requires C, 82.2; H, 12.7; N, 5.1%).

The Nopylamine–Boranes **16**.—BMS (2.00 cm^3, 20 mmol) in diethyl ether (5 cm^3) was added dropwise to a stirred solution of the nopylamine (20 mmol) in diethyl ether (20 cm^3) cooled in a bath at −20 °C. After the addition, the mixture was stirred at −20 °C for 30 min, allowed to warm to room temperature and then stirred for a further 30 min. The solvent and Me_2S were removed by evaporation under reduced pressure and the residue was kept under vacuum (0.05 Torr) for 2 h to give a near-quantitative yield of essentially-pure amine–borane.

(1R)-*Nopylpyrrolidine–borane*. This showed m.p. 49–50 °C after recrystallisation from hexane, $[\alpha]_D^{22}$ −33.2 (*c* 5.6, $CHCl_3$); δ_H 0.78 (s, 3 H), 1.09 (d, 1 H, *J* 8.6), 1.24 (s, 3 H), 1.84 (m, 2 H), 2.02 (m, 2 H), 2.16 (m, 4 H), 2.34 (m, 1 H), 2.44 (m, 2 H), 2.70 (m, 4 H), 3.16 (m, 2 H) and 5.24 (m, 1 H) (the BH_3 resonance was obscured); δ_C 21.15, 22.79, 26.18, 31.25, 31.63, 32.74, 37.96, 40.62, 45.81, 61.36, 62.18, 118.20 and 144.70; δ_B −12.8 (q, J_{BH} 93) (Found: C, 77.5; H, 12.3; N, 5.8. $C_{15}H_{28}BN$ requires C, 77.3; H, 12.1; N, 6.0%).

Unrecrystallised amine–borane of presumed e.e. 91% was used in the next stage to give **10**.

(1R)-N-*Nopyl*-N,N-*diethylamine–borane*. Viscous oil; δ_H 0.80 (s, 3 H), 1.11 (d, 1 H, *J* 8.70), 1.17 (t, 6 H, *J* 7.30), 1.25 (s, 3 H), 1.41 (br q, 3 H, J_{BH} 91, BH_3), 1.95–2.40 (complex, 8 H), 2.65 (m, 2 H), 2.77 (q, 4 H, *J* 7.30) and 5.26 (m, 1 H); δ_B −13.4 (q, J_{BH} 91).

(1R)-N-*Nopyl*-N,N-*diisobutylamine–borane*. Viscous oil; δ_H

0.79 (s, 3 H), 1.01 (d, 6 H, *J* 6.74), 1.02 (d, 6 H, *J* 6.46), 1.12, (d, 1 H, *J* 8.30), 1.25 (s, 3 H), 1.65–2.80 (complex, 16 H), 1.44 (br q, 3 H, J_{BH} 91, BH_3) and 5.23 (m, 1 H); δ_B −12.6 (q, J_{BH} 91).

The Polycyclic Amine–Boranes **10–12**.—The essentially pure nopylamine–borane **16** (*ca.* 20 mmol) was dissolved in toluene (25 cm^3) and heated under reflux for 14 h [$R_2 = (CH_2)_4N$], 16 h ($R_2N = Et_2N$) or 8 h ($R_2N = Bu^i{}_2N$). The solvent was removed under reduced pressure and the residue was purified by distillation to give 85–95% yields of **10** and **11**, which crystallised on standing; compound **12** decomposed during attempted distillation. For each of **10–12** the e.e. should be *ca.* 91%.

Compound **10**. B.p. 134–136 °C/0.03 Torr, m.p. 53–55 °C; $[\alpha]_D^{20}$ −7.1 (*c* 5.9, $CHCl_3$); δ_H 0.77 (d, 1 H, *J* 9.00), 1.18 (s, 3 H), 1.23 (s, 3 H), 1.46 (m, 2 H), 1.58–2.07 (complex, 12 H), 2.46 (m, 1 H), 2.78 (m, 4 H) and 3.25 (m, 2 H) (the broad BH_2 resonance was obscured); δ_B −1.47 (br t, J_{BH} *ca.* 74) (Found: C, 77.5; H, 11.9; N, 5.9. $C_{15}H_{28}BN$ requires C, 77.3; H, 12.1; N, 6.0%).

Compound **11**. B.p. 98–100 °C/0.05 Torr, m.p. 55 °C; $[\alpha]_D^{20}$ −21.1 (*c* 5.3, $CHCl_3$); δ_H 0.73 (d, 1 H, *J* 8.92), 1.04 (t, 3 H, *J* 7.33), 1.17 (s, 3 H), 1.18 (t, 3 H, *J* 7.30), 1.21 (s, 3 H), 1.38–2.04 (complex, 10 H) and 2.40–3.10 (complex, 7 H) (the broad BH_2 resonance was obscured); δ_B −2.25 (br t, J_{BH} *ca.* 73) (Found: C, 76.9; H, 13.1; N, 5.9. $C_{15}H_{30}BN$ requires C, 76.6; H, 12.9; N, 6.0%).

Compound **12**. This was a viscous oil which decomposed during attempted distillation with a bath temperature of 150 °C; it was judged to be essentially pure by NMR spectroscopy. $[\alpha]_D^{20}$ −9.2 (*c* 2.7, $CHCl_3$); δ_H 0.73 (d, 1 H, *J* 8.98), 0.99 (d, 3 H, *J* 6.77), 1.00 (d, 3 H, *J* 6.87), 1.02 (d, 6 H, *J* 6.80), 1.32–2.48 (complex, 13 H) and 2.62–2.98 (m, 6 H) (the broad BH_2 resonance was obscured); δ_B −2.11 (br t, J_{BH} *ca.* 70) (Found: C, 78.6; H, 13.4; N, 5.0. $C_{19}H_{38}BN$ requires C, 78.3; H, 13.2; N, 4.8%).

Substrates.—Racemic ethyl 3-hydroxybutyrate **24** and the (R)-(−)-enantiomer were obtained from Aldrich, as was racemic methyl (phenylsulfinyl)acetate **28**. Enantiomeric ratios for the hydroxybutyrate were determined using [Eu(hfc)$_3$] and observing its effect on the methyl group doublet (δ_H 1.22, *J* 6.45).

Racemic dimethyl 2,2-*dimethyl*-1,3-*dioxolane*-trans-4,5-*dicarboxylate* **17**. Compound **17** was prepared from racemic dimethyl tartrate[26] and 2,2-dimethoxypropane by the method of Carmack and Kelley;[27] b.p. 84–86 °C/0.13 Torr (lit.,[27] b.p. 82–90 °C/0.2 Torr); δ_H 1.50 (s, 6 H), 3.83 (s, 6 H) and 4.82 (s, 2 H). The (4*R*,5*R*)- and (4*S*,5*S*)-enantiomers were obtained from Fluka. The e.e. was determined in the presence of [Eu(hfc)$_3$] when the methoxy protons (δ 3.83) of the (*R*,*R*)-enantiomer are shifted to lower field than those of the (*S*,*S*)-enantiomer.

Racemic diisopropyl 2,2-*dimethyl*-1,3-*dioxolane*-trans-4,5-*dicarboxylate* **18**. Compound **18** was prepared from **17** and isopropyl alcohol in the presence of $Ti(OPr^i)_4$, m.p. 47–49 °C (from pentane–methanol);[28] δ_H 1,27 (d, 12 H, *J* 6.35), 1.48 (s, 6 H), 4.67 (s, 2 H) and 5.11 (septet, 2 H, *J* 6.35). The (4*R*,5*R*)- and (4*S*,5*S*)-enantiomers were prepared from the corresponding methyl esters. Enantiomeric ratios were determined using [Eu(hfc)$_3$], when the doublet at δ 1.27 separates into four peaks for each enantiomer.

Racemic methyl 2,2,5-*trimethyl*-1,3-*dioxolane*-trans-4-*carboxylate* **19**. Compound **19** was prepared from methyl crotonate using the literature route to the 2,2,5,5-tetramethyl analogue;[29] b.p. 38–40 °C/0.2 Torr (lit.,[30] b.p. 22 °C/0.08 Torr); δ_H 1.40 (d, 3 H, *J* 5.96), 1.41 (s, 3 H), 1.44 (s, 3 H), 3.76 (s, 3 H), 4.04 (d, 1 H, *J* 8.09) and 4.18 (dq, 1 H, *J* 8.10 and 5.95); δ_C 18.47, 25.67, 27.12, 52.31, 75.07, 80.35, 110.56 and 170.86. The (4*S*,5*R*)-enantiomer was obtained from Aldrich. Enantiomeric ratios were determined using [Eu(hfc)$_3$] when the singlet originally at δ 1.44 is shifted to lower field for the (4*S*,5*R*)-enantiomer than for its antipode.

Racemic methyl 5-*hydroxymethyl*-2,2-*dimethyl*-1,3-*dioxolane*-trans-4-*carboxylate* **20**. Compound **20** was prepared by the literature method[31] and purified by chromatography on silica gel (pentane–CH_2Cl_2–diethyl ether, 6:3:1 v/v eluent); δ_H 1.42 (s, 3 H), 1.46 (s, 3 H), 2.03 (dd, 1 H, *J* 8.55 and 4.62), 3.74 (ddd, 1 H, *J* 12.20, 8.55 and 3.74), 3.77 (s, 3 H), 3.93 (ddd, 1 H, *J* 12.20, 4.62, 3.03), 4.22 (m, 1 H) and 4.44 (d, 1 H, *J* 7.80); δ_C 25.62, 26.77, 52.49, 61.79, 74.87, 79.10, 111.39 and 171.20. The (4*R*,5*S*)-enantiomer was prepared from (4*R*, 5*R*)-**17**; $[\alpha]_D^{20}$ −7.8 (*c* 3.7, $CHCl_3$). Enantiomeric ratios were determined using [Eu(hfc)$_3$] when the singlet originally at δ 1.42 is shifted to lower field for the (4*S*,5*R*)-enantiomer than for its antipode.

Racemic 2-tert-*butyl*-1,3-*dioxolan*-4-*one* **21**. Compound **21** was prepared by condensation of trimethylacetaldehyde with glycolic acid. Powdered glycolic acid (2.03 g, 27 mmol), trimethylacetaldehyde (4.56 g, 53 mmol), toluene-*p*-sulfonic acid (0.2 g) and 1 drop of concentrated sulfuric acid in dichloromethane (60 cm^3) were heated under reflux for 6 h with azeotropic removal of water using a Dean and Stark apparatus. The residual solution was washed with water (30 cm^3) and the organic layer was dried ($MgSO_4$). The solvent was removed under reduced pressure and the residual oil was distilled to give the title compound **21** (2.76 g, 72%), b.p. 82–84 °C/20 Torr (lit.,[32] b.p. 60 °C/200 Torr, which appears to be in error); δ_H 0.95 (s, 9 H), 4.29 (AB q, 2 H) and 5.23 (s, 1 H); δ_C 23.24, 35.50, 64.45, 111.86 and 171.85. The enantiomers could be resolved by HPLC using a Chiralcel OD column (hexane eluent, UV detection at 230 nm).

Racemic dihydro-3-*methoxy*-4,4-*dimethylfuran*-2(3H)-*one* **22**. Compound **22** was prepared from (±)-pantolactone by the literature method,[33] b.p. 70–72 °C/3 Torr (lit.,[33] b.p. 92–93 °C/9.7 Torr); δ_H 1.05 (s, 3 H), 1.17 (s, 3 H), 3.55 (s, 1 H), 3.61 (s, 3 H), 3.86 (d, 1 H, *J* 8.92) and 3.95 (d, 1 H, *J* 8.92); δ_C 19.00, 23.1, 40.37, 59.35, 76.29, 83.68 and 175.04. The (*R*)-(+)-enantiomer was prepared from (*R*)-(−)-pantolactone, $[\alpha]_D^{25}$ + 48.5 (*c* 3.4, $CHCl_3$). Enantiomeric ratios were determined using [Eu(hfc)$_3$] when the two methyl resonances (δ 1.05 and 1.17) shift further downfield for the (*S*)-enantiomer than for its antipode.

Racemic dihydro-3-*trimethylsiloxy*-4,4-*dimethylfuran*-2(3H)-*one*. A mixture of (±)-pantolactone (1.80 g, 13.8 mmol) and *N*,*O*-bis(trimethylsilyl)acetamide (2.80 g, 13.8 mmol) in dichloromethane (10 cm^3) was heated under reflux for 2 h. The solvent was removed by evaporation under reduced pressure and the residue was purified by chromatography on silica gel (pentane–diethyl ether, 10:1 v/v eluent) to give the title compound **23** as a clear oil which solidified on storage at 5 °C; δ_H 0.17 (s, 9 H), 1.00 (s, 3 H), 1.09 (s, 3 H), 3.86 (d, 1 H, *J* 8.43), 3.95 (s, 1 H) and 3.96 (d, 1 H, *J* 8.43); δ_C −0.01, 18.98, 22.88, 40.67, 75.78, 76.40 and 175.87. The (*R*)-(+)-enantiomer was prepared from (*R*)-(−)-pantolactone, m.p. 41 °C; $[\alpha]_D^{25}$ +34.5 (*c* 3.6, $CHCl_3$) (Found: C, 53.6; H, 9.1. $C_9H_{18}O_3Si$ requires C, 53.4; H, 9.0%). Enantiomeric ratios were determined using either [Eu(hfc)$_3$] or [Eu(tfc)$_3$] when the Me_3Si resonance (δ 0.17) shifts further downfield for the (*S*)-enantiomer than for its antipode.

Racemic methyl ester of N-(tert-*butoxycarbonyl*)*proline* **25**. Compound **25** was prepared from (±)-proline by *N*-*tert*-butoxycarbonylation[34] followed by methyl esterification using methyl chloroformate in the presence of triethylamine and 4-dimethylaminopyridine,[35] b.p. 80–83 °C/0.2 Torr; smaller quanitities were purified by chromatography on silica gel (pentane–diethyl ether, 7:3 v/v eluent). Two amide rotamers were detected by NMR spectroscopy in the ratio *ca.* 2:1 at 25 °C. Major rotamer: δ_H 1.36 (s, 9 H), 1.81 (m, 1 H), 1.87 (m, 2

H), 2.15 (m, 1 H), 3.45 (m, 2 H) 3.67 (s, 3 H) and 4.16 (dd, 1 H, *J* 8.71 and 4.28); δ_C 23.58, 28.17, 30.76, 46.19, 51.83, 58.98, 79.68, 153.66 and 173.66. Minor rotamer; δ_H 1.41 (s, 9 H), 1.81 (m, 1 H), 1.87 (m, 2 H), 2.13 (m, 1 H), 3.31 (m, 2 H), 3.67 (s, 3 H) and 4.25 (dd, 1 H, *J* 8.49 and 2.30); δ_C 24.23, 28.31, 29.81, 46.44, 51.99, 58.59, 80.49, 150.30 and 173.40. The (*S*)-enantiomer was obtained in the same way from (*S*)-(−)-proline and purified by chromatography on silica gel. For the (*S*)-enantiomer in the presence of [Eu(tfc)$_3$], the single peak from the methoxy protons (originally at δ 3.67) resolved into two peaks, with that arising from the major rotamer shifted to lower field than that from the minor rotamer. The racemic material showed four peaks in this region; the peaks from the (*R*)-enantiomer appeared inside those from the (*S*). The e.e. of a partially resolved sample was estimated by comparison with the spectrum obtained from the racemic compound.

Racemic 3-tert-*Butyl* 4-*methyl* 2,2-*dimethyl*-1,3-*oxazolidine*-3,4-*dicarboxylate* **26**. Compound **26** was prepared as described for the separate enantiomers,[36] b.p. 85–88 °C/0.5 Torr [lit.,[36] 101–102 °C/2 Torr for the (*S*)-enantiomer]. Two amide rotamers were detected in $CDCl_3$ in the ratio *ca.* 3:2 at 25 °C. Major rotamer: δ_H 1.38 (s, 9 H), 1.52 (s, 3 H), 1.64 (s, 3 H), 3.72 (s, 3 H), 4.10 (m, 2 H) and 4.34 (dd, 1 H, *J* 7.01 and 2.96); δ_C 24.37, 24.94, 28.26, 52.27, 59.28, 66.25, 80.30, 95.03, 157.17 and 171.69. Minor rotamer: δ_H 1.46 (s, 9 H), 1.46 (5) (s, 3 H), 1.61 (s, 3 H), 3.72 (s, 3 H), 4.00 (m, 2 H) and 4.45 (dd, 1 H, *J* 6.59 and 2.31); δ_C 25.16, 26.01, 28.34, 52.39, 59.19, 66.00, 80.87, 94.39, 152.10 and 171.15. The (*S*)-enantiomer was prepared in the same way from (*S*)-(+)-serine. For the (*S*)-enantiomer in the presence of [Eu(tfc)$_3$], the single peak from the methoxy protons (originally at δ 3.72) resolved into two peaks with that arising from the major rotamer shifted to lower field than that from the minor rotamer. The e.e. of a partially-resolved sample was estimated by comparison with the spectrum obtained from the racemic compound in the presence of [Eu(tfc)$_3$], using the peaks arising from the minor rotamers of each enantiomer.

Racemic 1-(tert-*butoxycarbonyl*)-2-tert-*butyl*-3-*methylimidazolidin*-4-*one* **27**. Compound **27** was prepared from 2-*tert*-butyl-3-methylimidazolidin-4-one[37] and di-*tert*-butyl dicarbonate, following the procedure used for **26**,[36] m.p. 68–70 °C (from hexane); δ_H 0.98 (s, 9 H), 1.47 (s, 9 H), 3.74 (br d, 1 H, *J* 6.28), 4.11 (br s, 1 H) and 4.96 (br s, 1 H); δ_C 25.93, 28.22, 31.52, 39.53, 49.97, 82.34, 82.55 and 170.56 (the remaining carbonyl carbon resonance could not be detected). The (*R*)-(+)-enantiomer was obtained from Aldrich. The NMR spectra of the enantiomers could not be adequately resolved using [Eu(hfc)$_3$] or [Eu(tfc)$_3$] nor could the enantiomers be resolved by HPLC on Chiralcel OD. After kinetic resolution, residual **27** was isolated by chromatography on silica gel (pentane–CH_2Cl_2–diethyl ether, 3:3:1 v/v, followed by CH_2Cl_2–diethyl ether, 8:1 v/v eluent) and its e.e. was estimated by measurement of its optical rotation and comparison with the value reported[38] for the (*S*)-enantiomer, $[\alpha]_D$ −14.6 (*c* 1.18, CH_2Cl_2).

A sample of methyl (phenylsulfinyl)acetate **28** enriched in the (*R*)-(+)-enantiomer was prepared by a modified Sharpless oxidation of methyl (phenylthio)acetate using (+)-diethyl (2*R*, 3*R*)-tartrate as the source of chirality.[39] The sample showed $[\alpha]_D^{20}$ +53.0 (*c* 1.20, acetone); by HPLC on Chiralcel OD (hexane–Pr^{i}OH, 9:1 v/v eluent) the e.e. was found to be 37% and using (*S*)-(+)-DNPB shift reagent it was found to be 38%. For an e.e. of 64% Duñach and Kagan[40] found $[\alpha]_D^{20}$ +98 (*c* 1, acetone), equivalent to +58 for an e.e. of 38%.

Kinetic Resolutions.—A detailed description of the procedure for carrying out kinetic resolutions has been given previously.[2] The light source for photolysis was a 160 W medium-pressure discharge lamp (Heraeus). The substrate concentration was typically *ca.* 1.0 mol dm^{-3} and the catalyst concentration was *ca.* 0.2 mol dm^{-3} for **4** and **5** and *ca.* 0.4 mol dm^{-3} for **6**–**12**.

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