Homolytic Reactions of Ligated Boranes. Part 16.[1] Enantioselective Hydrogen-atom Abstraction by Chiral Amine–Boryl Radicals: Catalytic Kinetic Resolution of Esters and of Camphor

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UV irradiation of an oxirane solution containing di-*tert*-butyl peroxide, an amine–alkylborane complex (in which the *B*-alkyl group is optically active) and a racemic ester or camphor as substrate, gives rise initially to the *tert*-butoxyl radical which rapidly abstracts hydrogen from the complex to form an optically active amine–boryl radical. The amine–boryl radical then abstracts hydrogen enantioselectively from a C–H group α to the carbonyl group in the substrate to regenerate the amine–alkylborane. This abstraction reaction has been used to bring about catalytic kinetic resolution of the substrate, using the bis(isopinocampheylborane) complex of *N,N,N′,N′*-tetramethylethylenediamine and some of its derivatives as catalysts. After partial consumption of the substrate, the amount remaining and its enantiomeric excess (ee) have been used to derive enantioselectivity constants for hydrogen-atom abstraction. Enantioselectivity varies considerably with the structure of the substrate. The highest selectivity was observed for hydrogen abstraction from dimethyl 2,2-dimethyl-1,3-dioxolane-*trans*-4,5-dicarboxylate, when after 75% consumption of initially-racemic ester at −90 °C, the residual substrate showed an ee of 97%. A transition-state model is proposed to account for the observed enantioselectivities.

Although many stereoselective radical reactions are now known, fewer enantioselective homolytic processes have been identified and enantioselective atom-transfer reactions are particularly uncommon. Enantioselective hydrogen-atom transfer has been observed previously when chiral alkoxyl,[2] nitroxyl,[3,4] or amine–boryl[5,6]† radicals abstract from asymmetric substrates and when an asymmetric dihydronicotinamide donates hydrogen to the radical anion of a prochiral ketone.[7]

We have previously shown how the sluggish abstraction of electron-deficient hydrogen atoms by electrophilic alkoxyl radicals can be promoted by amine–borane complexes, which act as donor polarity reversal catalysts.[1,8,9] For example, *tert*-butoxyl radicals abstract hydrogen relatively slowly from an α-C–H group in an ester [eqn. (1)], because of adverse polar effects in the transition state. However, in the presence of an amine–borane **1**, the single-step reaction (1) is replaced by the catalytic cycle of reactions (2) and (3), both of which benefit from favourable charge-transfer interactions in the transition state. If the amine–boryl radical **2** is optically active, *e.g.* if the amine moiety or the *B*-alkyl group R is chiral, then the hydrogen abstraction step (3) can be enantioselective and the overall hydrogen-atom transfer to Bu^{t}O$^\bullet$ also becomes enantioselective, with the optically active amine–borane complex acting as a potentially-recyclable catalyst.

$$Bu^tO^\bullet + H\text{–}\underset{|}{\overset{|}{C}}\text{–}CO_2Me \xrightarrow{slow} Bu^tOH + >\dot{C}\text{–}CO_2Me \quad (1)$$

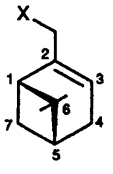
$$Bu^tO^\bullet + amine{\rightarrow}BH_2R \xrightarrow{fast} Bu^tOH + amine{\rightarrow}\dot{B}HR \quad (2)$$
1 **2**

$$amine{\rightarrow}\dot{B}HR + H\text{–}\underset{|}{\overset{|}{C}}\text{–}CO_2Me \xrightarrow{fast} amine{\rightarrow}BH_2R + >\dot{C}\text{–}CO_2Me \quad (3)$$
3

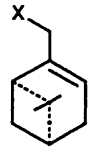
In this paper we describe the use of optically active amine–alkylboranes, which contain a chiral *B*-alkyl group, as catalysts for the kinetic resolution of a variety of esters and camphor by enantioselective abstraction of hydrogen from their electron deficient α-C–H groups. Part of this work has appeared in preliminary form.[5,6]

Results and Discussion

The 1:2 complexes of *N,N,N′,N′*-tetramethylethylenediamine (TMEDA) with isopinocampheylborane[10–13] and with some of its derivatives[14] were chosen as polarity reversal catalysts for our initial work. The boranes were prepared by hydroboration of optically active α-pinene (**4** or **5**) or the 2-substituted apopinenes **6**–**8**, which are readily available from natural sources.[14–20] The use of chiral organoboranes of this type for asymmetric synthesis, based on heterolytic reactions, is well established.[21,22]



4; X = H



5; X = H
6; X = Me
7; X = CH_2OMe
8; X = CH_2OCH_2Ph
9; X = CH_2OH

† In a preliminary communication[5] we inadvertently overlooked two previous reports[2,3] of enantioselective hydrogen-atom transfer. We are grateful to Professor M. J. Perkins for drawing our attention to this oversight.

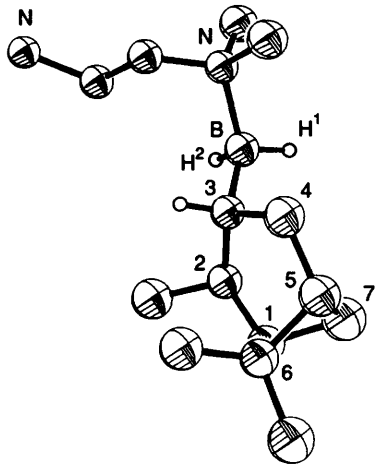
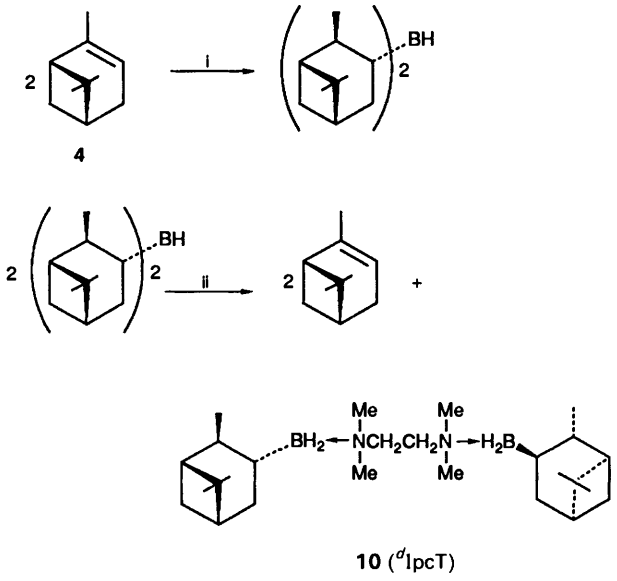


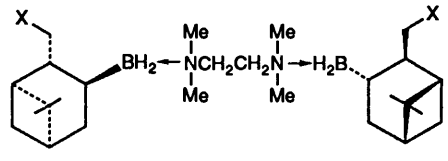
Fig. 1 Partial structure of ^{d}IpcT in the crystal, drawn using the co-ordinates given in ref. 24

Treatment of (1*R*)-(+)-α-pinene **4** with borane–methyl sulfide complex (BMS) in refluxing diethyl ether gives diisopinocampheylborane. Subsequent addition of 0.5 molar equiv. of TMEDA gives the complex **10** by displacement of α-pinene, as described by Brown and his co-workers[10–13] (see Scheme 1). Corresponding bis(alkylborane)–TMEDA complexes **11–14** were prepared from the other pinenes **5–8**. The



10 (^{d}IpcT)

Scheme 1 *Reagents and conditions:* i, $Me_2S{\rightarrow}BH_3$, ether, reflux; ii, TMEDA

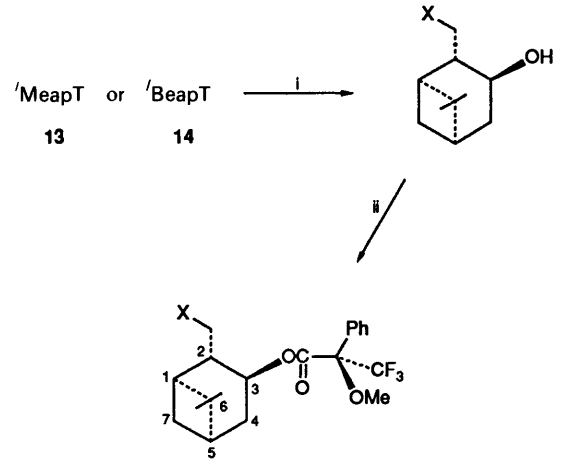


11: X = H (^{l}IpcT)
12: X = Me (^{l}EapT)
13: X = CH_2OMe (^{l}MeapT)
14: X = CH_2OCH_2 (^{l}BeapT)

acronyms, given in parentheses after the structures, indicate that the complex contains the isopinocampheyl (Ipc), iso-2-ethylapopinocampheyl (Eap), iso-2-(2-methoxyethyl)apopinocampheyl (Meap) or iso-2-(2-benzyloxyethyl)apopinocampheyl (Beap) group attached to boron, and the superscript *d* or *l* indicates whether the starting pinene was *dextro-* or *laevo-*rotatory, following the conventions adopted by Brown *et al.*[14,16,19,23] *syn*-Hydroboration takes place in an anti-Markovnikov sense from the less hindered face of the pinene (opposite from the 6,6-dimethyl bridge) to give a product of well-defined stereochemistry.[19,21] The samples of (1*R*)-(+)- and (1*S*)-(−)-α-pinene used in this work were each almost enantiomerically-pure [> 99% enantiomeric excess (ee)]. However, it has been reported that when ^{d}IpcT **10** is prepared from (+)-α-pinene of lower enantiomeric purity (*ca.* 91% ee), the ee of the complex may be enhanced to *ca.* 100% by crystallisation from diethyl ether.[10] The structure of ^{d}IpcC has been determined by X-ray crystallography (Fig. 1).[24]

Contrary to reports in the literature,[10–13] in our hands ^{d}IpcT did not melt cleanly at 140–141 °C and, in either a sealed or open tube, the behaviour of this compound depended on the rate of heating. Even when the complex was transferred to the preheated apparatus at 110 °C and then heated at 2 °C min^{-1}, the crystals began to melt at *ca.* 120 °C: solid was still present until *ca.* 145 °C and melting was accompanied by slow evolution of a gas (presumably hydrogen). We conclude that ^{d}IpcT is thermally unstable at or below its melting point: the other complexes **11–14** behaved in a qualitatively similar way on heating.

The pinenes **6–8** were prepared from (1*R*)-(−)-nopol **9**, which is available commercially with an ee of *ca.* 90%. The complex ^{l}EapT **12** is upgraded to 99–100% ee by crystallisation from ether.[14] The complexes ^{l}MeapT **13** and ^{l}BeapT **14** have not been described previously and their enantiomeric purities were determined by oxidation with alkaline hydrogen peroxide,[10,14,20,25] followed by reaction of the derived alcohol with (*S*)-(+)-2-methoxy-2-phenyl-3,3,3-trifluoropropanoyl chloride[26,27] (Mosher's acid chloride) **15** and measurement by ^{1}H and ^{19}F NMR spectroscopy of the diastereoisomeric composition of the ester **16** or **17** (see Scheme 2 in which only

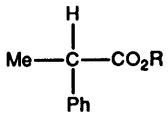


16: X = CH_2OMe
17: X = CH_2OCH_2Ph

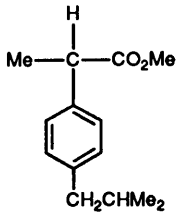
Scheme 2 *Reagents* i, H_2O_2/HO^-; ii, (*S*)-(+)-PhC(OMe)(CF_3)COCl **15**/Et_3N

the major enantiomer of the pinanol is shown). Direct hydroboration/oxidation of the pinenes **7** and **8** provided *ca.* 95:5 diastereoisomeric mixtures of the Mosher esters for comparative purposes. After two recrystallisations from hexane–diethyl ether (1:1), ^{l}BeapT prepared from **8** (89% ee) was upgraded to ≥ 98.5% ee, while ^{l}MeapT was upgraded much more slowly by recrystallisation from hexane–diethyl ether (2.5:1) and the ee of the complex used as a catalyst in this work was 91%.

Kinetic Resolution of Esters.—The esters **18–26** and camphor



18; R = Me
19; R = Et
20; R = Bu^t



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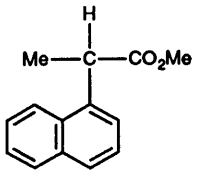
27 have been examined in an initial attempt to identify some of the factors which influence the enantioselectivity of α-hydrogen-atom abstraction by chiral amine–boryl radicals. [The (4*S*,5*S*) and (1*S*) enantiomers are shown for **26** and **27**, respectively].



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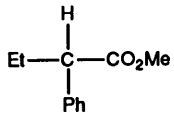

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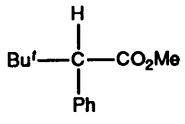

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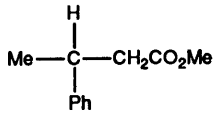

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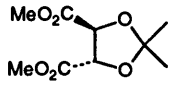

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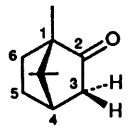

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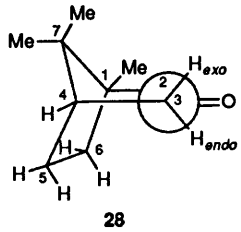
Typically, samples consisted of the racemic substrate (*ca.* 0.8 mol dm^{-3}), di-*tert*-butyl peroxide (DTBP; *ca.* 25% v/v), amine–borane catalyst (*ca.* 0.15 mol dm^{-3}) and *tert*-butylbenzene (*ca.* 0.5 mol dm^{-3}) as an internal standard for GLC analysis. The solvent was usually oxirane, chosen because amine–boranes have adequate solubilities at low temperatures and because of its relatively low reactivity (for an ether containing α-C–H groups) towards hydrogen-atom abstraction by alkoxyl radicals. Samples were sealed in evacuated quartz tubes and irradiated at −60–−90 °C with unfiltered light from either a high-pressure (250 W) or a medium-pressure (150 W) mercury discharge lamp. *tert*-Butoxyl radicals, generated by photochemical cleavage of DTBP, reacted rapidly with the amine–borane catalyst **1** to form the amine–boryl radical **2** which then abstracted hydrogen from the ester [reactions (2) and (3)]. The fate of the α-carbonylalkyl radical **3** is important since, if efficient kinetic resolution is to be achieved, the major route for its decay should not be by abstraction of hydrogen to regenerate racemic ester.

After partial consumption of the ester or camphor, the amount remaining was determined by GLC analysis, the residual substrate was isolated chromatographically (column or HPLC), and its enantiomeric composition was determined by ^{1}H NMR spectroscopy using an optically active lanthanide shift reagent [(+)-Eu(hfc)$_3$]* and/or by HPLC analysis using a chiral stationary phase. When both analytical methods were used, the ee's determined were the same within experimental accuracy (± 0.5%). Assignments were made by comparison with authentic samples of esters of known absolute configuration.

If none of the α-carbonylalkyl radicals **3** produced in reaction (3) go on to abstract hydrogen unselectively and regenerate racemic substrate, the enantioselectivity factor *s* will be given by eqn. (4).[28,29] Here k_A and k_B are the rate constants for abstraction of hydrogen from the faster- and the slower-reacting enantiomer, respectively, *C* is the fraction of substrate consumed, and *EE* is the fractional ee of the substrate which remains. Control experiments (see below) with methyl 2-phenylpropanoate **18** showed that some racemisation of nearly optically-pure substrate does take place under the conditions used for the kinetic resolution. Presumably this occurs because some of the α-carbonylalkyl radicals *do* decay by radical–radical disproportionation reactions and the importance of this mode of decay will vary from system to system. Hence, the values of *s* obtained using eqn. (4) will be lower limits. Hydrogen-atom transfer to the α-carbonylalkyl radical would not cause a problem if this radical were to be trapped rapidly in another type of reaction, for example by addition to a carbon–carbon double bond.[8d] The results of representative kinetic resolutions are summarised in Table 1.

$$s = (k_A/k_B) = \ln[(1 - C)(1 - EE)]/\ln[(1 - C)(1 + EE)] \quad (4)$$

Hydrogen-atom abstraction by amine–boryl radicals from camphor **27** takes place from C-3, as shown by EPR studies.[1] † For steric reasons, it would be expected that the *endo*-hydrogen atom will be abstracted more readily than that in the *exo*-position; any stereoelectronic effect of the adjacent carbonyl group should influence abstraction of the two hydrogen atoms to approximately equal extents (see structure **28**).



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The enantiomeric composition of camphor could not be determined accurately either by NMR spectroscopy using a chiral shift reagent or by HPLC using the chiral stationary phases at our disposal.[30,31] It was therefore converted to the 2,4-dinitrophenylhydrazone (DNP) derivative, the enantiomers of which were well-separated by chiral-stationary-phase HPLC.‡ Commercial samples of 'racemic' camphor reproducibly showed a small excess of one enantiomer [*ca.* 1–2% ee of (1*R*)-(+) from Aldrich and of (1*S*)-(−) from Lancaster Synthesis (*cf.* ref. 30)]. Since these results do not appear to be artifacts of the analytical method and were supported by the small optical rotations shown by the parent camphors, the values of *s* given in Table 1 were calculated using eqn. (5), in which *R* is equal to the enantiomeric ratio [B]/[A] at the start of the resolution.

$$s = (k_A/k_B) = \ln[(1 - C)(1 - EE)(1 + R)/2]/\ln[(1 - C)(1 + EE)(1 + R)/2R] \quad (5)$$

The temperature dependence of *s* should be described by the Arrhenius eqn. (6), in which *E* is the activation energy, *A* is the

* Tris[3-(heptafluoropropylhydroxymethylene)-(+)-camphorato] europium(III).

† The EPR spectrum of the derived α-carbonylalkyl radical shows *a*(1 H$_\alpha$) 19.0, *a*(1 H$_\beta$) 8.3, *a*(1 H$_\gamma$) 4.8 G and *g* 2.0041 in cyclopropane at −85 °C; further unassigned hyperfine structure was also present. The radical was generated using the techniques described previously[1,8a–c] under conditions of polarity reversal catalysis.

‡ No complications from possible geometric isomerism of the hydrazone were encountered during HPLC analysis. Authentic samples of DNP derivatives prepared from (1*R*)-(+)- and (1*S*)-(−)-camphor gave only single peaks.

Table 1 Results from representative kinetic resolutions of racemic esters and of camphor in oxirane

Entry	Substrate	Catalyst	T/°C	Irradiation time[a,b]/min	Substrate consumption (%)	More reactive enantiomer	ee of residual substrate (%)[c]	Enantioselectivity factor s[d]
1	**18**	^{d}IpcT	−83	300	41.0	*R*	22.0 (*S*)	2.4
2	**18**	^{d}IpcT	−67	300	54.5	*R*	30.2 (*S*)	2.2
3	**18**	^{l}IpcT	−67	300	52.9	*S*	28.5 (*R*)	2.2
4	**18**	^{l}EapT	−77	300	14.7	*S*	10.4 (*R*)	4.5
5	**18**	^{l}MeapT	−77	300	41.3	*S*	22.0 (*R*)	2.3[e]
6	**18**	^{l}BeapT	−77	300	25.4	*S*	17.8 (*R*)	3.8
7	**19**	^{d}IpcT	−77	300	49.3	*f*	27.4	2.3
8	**20**	^{d}IpcT	−77	300	29.1	*f*	22.5	4.2
9	**21**	^{d}IpcT	−72	300	46.5	*R*	23.2 (*S*)	2.1
10	**21**	^{l}IpcT	−72	300	48.9	*S*	27.7 (*R*)	2.3
11	**21**	^{l}BeapT	−77	300	21.9	*S*	8.8 (*R*)	2.1
12	**22**	^{d}IpcT	−77	300	14.7	*f*	4.0	1.7
13	**23**	^{d}IpcT	−77	300	10.5	*R*	7.0 (*S*)	4.2
14	**23**	^{l}IpcT	−77	300	18.2	*S*	14.3 (*R*)	5.3
15	**25**	^{d}IpcT	−72	300	48.4	*S*	12.7 (*R*)	1.5
16	**25**	^{l}IpcT	−72	300	50.8	*R*	10.5 (*S*)	1.3
17	**26**	^{d}IpcT	−90	15	42.8	*S,S*	58.4 (*R,R*)	14.6
18	**26**	^{l}IpcT	−90	15	47.0	*R,R*	64.5 (*S,S*)	12.2
19	**26**	^{d}IpcT	−90	25	75.0	*S,S*	96.6 (*R,R*)	(6.7)[g]
20	**27**	^{d}IpcT	−73	150[h]	52.0	*S*	12.8 (*R*)	1.5[i]
21	**27**	^{l}IpcT	−73	100[h]	38.8	*R*	10.4 (*S*)	1.5[i]
22	**27**	^{l}MeapT	−73	150[h]	33.2	*R*	6.8 (*S*)	1.3[e,i]
23	**27**	^{l}BeapT	−73	150[h]	38.5	*R*	3.6 (*S*)	1.1[i]

[a] The 250 W high-pressure mercury-lamp was used, unless stated otherwise. [b] With the aromatic substrates **18**–**25**, the sample developed a pronounced yellow colouration during irradiation; this resulted in unproductive light absorption and necessitated the long irradiation times. [c] Enantiomer present in excess shown in parentheses. [d] Calculated using eqn. (4) or (5), as appropriate. [e] The ee of the ^{l}MeapT was only 91%. The value of s obtained using enantiomerically pure catalyst would be slightly larger. [f] Not determined. [g] Under these experimental conditions, the value of s calculated from C and EE will be a gross underestimate. [h] Light source was the 150 W medium-pressure mercury lamp, see text. [i] Starting camphor consisted of 49.4% (1*R*)-(+) and 50.6% (1*S*)-(−).

pre-exponential factor and T is the absolute temperature. The value of s would be expected to increase with decreasing temperature and the activation energy difference ($E_B - E_A$) can be determined from the temperature dependence of s. However,

$$s = (k_A/k_B) = (A_A/A_B)\exp(E_B - E_A)/RT \qquad (6)$$

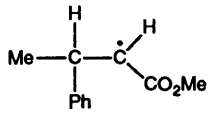
more accurate measurements of s over a wider range of temperatures and using a more quantitative technique[6] than that employed here would be required to determine (A_A/A_B) and ($E_B - E_A$) separately. If (A_A/A_B) is taken to be unity, then s values of 2–20 at −75 °C correspond to activation energy differences ($E_B - E_A$) of 1.1–4.9 kJ mol^{-1}.

When optically active isopinocampheylborane or its derivatives hydroborate prochiral alkenes, the extent of asymmetric induction is sensitive to the steric requirement of the substituent at the 2-position of the isoapopinocampheyl ring, although the effects are not large.[21] For example,[14] EapBH$_2$ gives greater asymmetric induction than does IpcBH$_2$ in the hydroboration of medial alkenes. Similarly, reduction of prochiral ketones by lithium *B*-alkyl-9-borabicyclo[3.3.1]nonyl hydrides[15–17] or by chiral dialkyl(chloro)boranes[19] generally proceeds with a greater degree of asymmetric induction when the *B*-alkyl group is Eap or Beap than when it is Ipc. Changing the steric requirement of the 2-substituent on the isoapopinocampheyl moiety in the TMEDA–borane complex has an effect of similar magnitude on the enantioselectivity of hydrogen-atom abstraction (see Table 1).

If a kinetic resolution is to yield useful quantities of substrate with a high ee, the value of s must be *ca.* 5 or greater.[28,29] With IpcT catalyst, increasing the bulk of the *O*-alkyl group in the 2-phenylpropanoate esters from Me in **18** to Bu^t in **20** causes s to increase from 2.3 to 4.2, to approach the critical value required.

2-(4-Isobutylphenyl)propanoic acid is the well-known anti-inflammatory drug Ibuprofen[32] and its methyl ester **21** showed a value of s similar to that obtained for the unsubstituted compound **18**. Exchanging the phenyl group in **18** for a 1-naphthyl group (compound **22**) caused a small decrease in s. Increasing the bulk of the α-alkyl group from Me in **18** to Et in **23** resulted in a significant increase in s, but the photochemical reaction became very sluggish and only a low conversion was achieved. This could be because H-atom abstraction is retarded by the more bulky ethyl group and/or because the α-carbonylalkyl radicals produced undergo predominant disproportionation,[33] rather than combination as in the case of the α-Me analogue.[33–35] In addition to regenerating racemic substrate, disproportionation would give the unsaturated ester MeCH=C(Ph)CO$_2$Me, to which amine–boryl radicals would add very readily because of favourable polar effects.[36] The α-*tert*-butyl analogue **24** did not react under the normal conditions and this must be the result of steric hindrance to H-atom abstraction by the amine–boryl radical; disproportionation of the derived α-carbonylalkyl radical is not now possible.

Amine–boryl radicals abstract hydrogen only from the α-carbon atom of methyl 3-phenylbutanoate **25**, as judged by EPR spectroscopy.[1,8a–c,*] The diastereotopic α-hydrogen atoms in **25** are non-equivalent; the asymmetric centre is retained in the derived radical **29** and its reaction products will



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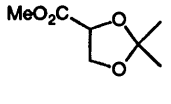


30

* The EPR spectrum of **29** shows a(1 H$_\alpha$) 20.4, a(1 H$_\beta$) 9.8 G and g 2.0034 at −65 °C in cyclopropane; further splittings arising from long-range hyperfine coupling were observed and line distortions indicated the probable presence of two rotameric forms.

be optically active if the initial H-atom abstraction is enantioselective. Considering that abstraction takes place from the carbon adjacent to the asymmetric centre, the value of *s* is encouragingly large.

α-Hydrogen-atom abstraction from the isopropylidene tartrate **26** takes place with high enantioselectivity (entries 17 and 18) and in an experiment when 75% of the tartrate was consumed (entry 19), the ee of the residual ester was 97%. The lower value of *s* obtained from the latter data is not surprising considering the sensitivity of *s* to *C* and *EE* when *s* is relatively large and the fact that *C* and *EE* provide only an indirect measure of *s* using eqn. (4). This high enantioselectivity has been confirmed by independent EPR studies of the individual abstraction steps in isolation.[6] It is noteworthy that the EPR method for determining *s* is direct and is not affected by the fate of the α-carbonylalkyl radicals, since relative rates are determined at effectively zero substrate consumption.[6] Corresponding EPR studies of the ester **30** give a much lower value of *s* (2.5 at −85 °C) for abstraction by the amine–boryl radical derived from IpcT.[6] The structural features which result in the relatively large value of *s* for abstraction from **26**, such as the presence of a second asymmetric centre adjacent to the site of reaction (*cf.* ref. 37) and the marked differences in bulk of the substituents attached to C_α (see later), merit detailed investigation.

Although the value of *s* obtained for hydrogen-atom abstraction from camphor is too small to be practically useful with the present amine–borane catalysts, little effort has yet been put into catalyst design and substantial improvements might be anticipated.

Control Experiments.—Experiments were carried out in order to confirm that kinetic resolution is brought about by enantioselective hydrogen-atom abstraction by optically active amine–boryl radicals, and to assess the extent of substrate racemisation under the reaction conditions. Unless stated otherwise, the sample temperature was −77 °C, the light source was the 250 W high-pressure mercury lamp and the irradiation time was 300 min.

With (±)-*methyl* 2-*phenylpropanoate* **18**. Without any amine–borane catalyst, 96% of the original ester remained after irradiation for 200 min, showing that the *tert*-butoxyl radical preferentially abstracts hydrogen from the oxirane solvent.[5] In the presence of the achiral amine–borane catalyst $Me_3N{\rightarrow}BH_2Bu$, 49% of the ester was consumed after 180 min irradiation and the residual substrate was racemic. In the presence of ^{d}IpcT catalyst, but without DTBP, essentially no ester was consumed and the recovered ester was racemic. Repetition of the last experiment in the presence of *tert*-butyl alcohol (20 mol% of the ester) gave the same result.

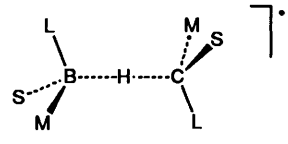
With (R)-(−)-*methyl* 2-*phenylpropanoate.* The ester contained a 94% ee of the (*R*)-(−)-enantiomer and the enantiomeric composition was unaltered by the washing and chromatographic procedures used for isolation of residual ester after kinetic resolution. After irradiation of a sample containing (*R*)-ester, ^{d}IpcT catalyst and DTBP in the usual way, 60% of the ester had been consumed; the residual ester consisted of 85% (*R*)- and 15% (*S*)-enantiomer. Since the (*S*)-ester is the slower reacting enantiomer towards the amine–boryl radical derived from ^{d}IpcT, this experiment has the best chance of detecting enantiomer interconversion under the conditions of kinetic resolution. Clearly some interconversion does take place.

With (4*S*,5*S*)-(+)-*dimethyl* 2,2-*dimethyl*-1,3-*dioxolane*-trans-4,5-*dicarboxylate* **26**. This is more reactive than the (4*R*,5*R*)-enantiomer towards the amine–boryl radicals from ^{d}IpcT. After 20 min irradiation at −90 °C under the usual conditions, 51% of the ester had been consumed. The residual ester contained a barely-detectable amount (< 0.3%) of the (4*R*,5*R*)-enantiomer; its absence is understandable since its formation requires inversion at both asymmetric centres, which would probably have to take place *via* the intermediacy of the *cis*-(*meso*)-isomer.[6]

With (±)-*camphor.* Irradiation was carried out at −73 °C for 150 min with light from the 150 W medium-pressure mercury lamp; the starting camphor contained a 1.2% ee of the (1*S*)-(−)-enantiomer. A possible problem here could be an enantioselective reaction of photo-excited camphor with the amine–borane. Without DTBP, 20% of the camphor was indeed consumed, but the residual material had the same enantiomeric composition as the starting camphor. In the presence of DTBP (which would screen the camphor) with $Me_3N{\rightarrow}BH_2Bu$ catalyst, 39% of the camphor was consumed and the remaining substrate showed a 1.4% ee in favour of (1*S*)-camphor.

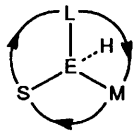
Model for Enantioselective Hydrogen-atom Abstraction.—It is clearly important to develop a transition-state model which will account for the absolute stereochemical course of enantioselective H-atom transfer and also facilitate the rational design of new catalysts which will be more generally applicable and show greater chiral discrimination than those used in the present work. For steric and electronic reasons, it is likely that abstraction of hydrogen from four-co-ordinate carbon by an amine-boryl radical will proceed through a transition state in which the preferred geometry of the B • • • H • • • C fragment is near-to linear, although distortion from the optimum angle would not be expected to result in a large increase in activation energy.[38]

If long-range torsional/steric interactions between the substituents on the boron and carbon atoms are dominant in determining the preferred transition state conformation, the latter should be of the staggered type **31**, in which the symbols L, M and S refer to substituents of large, medium and small effective bulk.

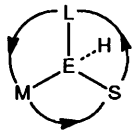


31

If we define *steric chirality*, by analogy with the Cahn-Ingold-Prelog[39] conventions for describing absolute stereochemistry, using the priority sequence L > M > S, then a boron-centre of steric chirality **32a** (ρ) will give a lower-energy transition state when associated with a carbon-centre of steric chirality **32b** (σ) than with a centre of steric chirality ρ (E = B or C).



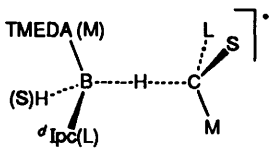
32a (ρ)



32b (σ)

Inspection of the crystal structure determined for ^{d}IpcT by Soderquist *et al.*[24] and shown partially in Fig. 1, suggests that the hydrogen atom being transferred from C to B will be in a position similar to that occupied by H^1, rather than that occupied by the more sterically encumbered H^2. Thus, the configuration at the boron-centre in the transition state for abstraction catalysed by this enantiomer of the amine–borane will be σ, as shown in **33**, The preferred steric chirality at the carbon-centre will thus be ρ, as shown.

When assessing the effective bulk of substituents attached to carbon, stereoelectronic effects must be considered, since in the



33

Table 2 Steric chiralities of substrate enantiomers which are the more reactive towards the amine–boryl radical derived from ^{d}IpcT

Substrate	More reactive enantiomer	Steric chirality
18	*R*	ρ[a]
21	*R*	ρ[a]
23	*R*	ρ[a]
25	*S*	ρ[b]
26	*S,S*	ρ[c]
27	*S*	ρ[d]

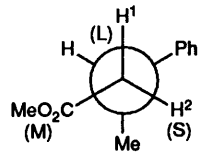
[a] Assuming substituent size CO_2Me > Ph, *p*-$Bu^tC_6H_4$ > Me, Et. [b] See text. [c] Assuming substituent size C(H)(OR)CO_2Me > CO_2Me > $OC(OR)Me_2$. [d] Assuming substituent size $C(H)(CH_2R)CMe_2R$ > $C(=O)CMeR_2$ > H.

transition state carbonyl groups, alkoxy groups and aromatic rings will presumably adopt conformations in which overlap is optimised between their π systems and the developing semi-occupied orbital on C_α.

For the rigid tartrate **26** and camphor **27**, molecular models indicate that the (4*S*,5*S*)- and (1*S*)-enantiomers possess ρ steric chirality at C_α and thus these enantiomers should react more rapidly than their antipodes with the amine–boryl radical derived from ^{d}IpcT, in accord with experiment (see Table 2). For the related ester **30**, the difference in bulk of the large (CH_2OR) and medium (CO_2Me) substituents attached to C_α is much less than for **26**, in accord with the smaller value of *s* found for the former ester.[6]

For many of the substrates resolved in this work it is not straightforward to decide on the steric chirality at C_α. If the assumptions are made that the effective C_α-substituent sizes in the transition state are CO_2Me > Ph, *p*-$Bu^tC_6H_4$ > Me, Et for the acyclic esters **18**, **21** and **23**, then the steric chiralities of the enantiomers which are found to react more rapidly with the amine–boryl radical derived from ^{d}IpcT will be those shown in Table 2. These steric chiralities are all ρ, in accord with the predictions of the steric-strain model.

For the ester **25** the preferred conformation about the C_α–C_β bond is likely to be that shown in **34** for the (*S*)-enantiomer.



34

This conclusion is consistent with the experimental values of $^3J_{HH}$ (8.3 and 6.9 Hz at 20 °C, 8.4 Hz and 7.0 Hz at −50 °C in $CDCl_3$ solvent), although the conformation in which the *C*-Me group is *anti* to the ester function is evidently also appreciably populated. On steric grounds, the more accessible H^1 should be abstracted more readily than H^2 and, assuming that the substituent sizes in the transition state are PhC(H)Me = L, MeO_2C = M and H = S, the steric chirality of **34** is ρ. Thus, the prediction of the steric-strain model is that the (*S*)-enantiomer of **25** should react more rapidly when ^{d}IpcT is the catalyst, as is observed by experiment (see Table 2).

Several directions for future development can be identified. Further work with rigid substrates is required to test the predictions of the steric-strain model. The extent to which the remaining R^*BH_2 group in the amine–boryl radical derived from $(R^*BH_2)_2$·TMEDA influences the enantioselectivity of hydrogen-atom transfer to the $R^*\dot{B}H$ moiety also remains to be investigated. In general, dipole–dipole interactions could be important for reactants which contain the strongly polar $^{\delta+}N\rightarrow B^{\delta-}$ linkage. Optically active amine–boranes with more rigid and varied[40,41] structures need to be synthesised. Some means of tethering[41] the substrate to the amine–boryl radical or to its parent amine–borane need to be developed, so that hydrogen-atom transfer takes place within a loose complex and becomes effectively intramolecular with concomitant increases in rate and stereoselectivity. Such tethering could be accomplished by means of hydrogen bonding or by Lewis acid complexation with a carbonyl group in the substrate, as has been invoked by Corey *et al.*[41a,b] to explain the very high enantioselectivities observed in reduction of ketones by borane complexes of oxazaborolidines.

Future work must also aim to incorporate catalytic enantioselective hydrogen-atom abstraction into a chain reaction sequence,[8d] such that both kinetic resolution of starting material and enantio- or diastereo-selective product formation can be accomplished in a radical chain process.

Experimental

NMR spectra were recorded using a Varian VXR-400 instrument (400 MHz for ^1H). The solvent was $CDCl_3$ and chemical shifts are reported relative to Me_4Si internal standard (^1H) or trifluoroacetic acid external standard (^{19}F); *J*-values are quoted in Hz. GLC analyses were carried out using a Pye-Unicam 204 chromatograph equipped with a flame-ionisation detector and a Hewlett-Packard model 3392A integrator. A glass column (2 m × 4 mm bore) 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. The achiral stationary phase was Nucleosil 5 μm silica gel (analytical and preparative) and Chiralcel OD (Daicel Chemical Industries) was used to effect analytical separation of enantiomers. The mobile phases were hexane–ethyl acetate mixtures (achiral) or hexane–isopropyl alcohol mixtures (Chiralcel OD). 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.

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. *tert*-Butylbenzene and TMEDA were distilled from calcium hydride. Boron trifluoride–methanol complex (50% BF_3 in excess methanol), BMS (10 mol dm^{-3} solution in excess Me_2S), (+)-Eu(hfc)$_3$, and (*R*)-(+)-2-methoxy-2-phenyl-3,3,3-trifluoropropanoic acid (Mosher's acid) (all Aldrich), and oxirane (Fluka) were used as received. The sources and enantiomeric compositions of the pinene derivatives used in this work are given in Table 3.

† However, pure crystalline IpcT was unchanged after exposure to the atmosphere for 12 h at room temp.[1] The complexes ^{t}MeapT and ^{t}BeapT were appreciably more moisture-sensitive than IpcT or ^{t}EapT.

Table 3 Properties of pinene derivatives **4–9**

Pinene	Source/lit. prepn.	B.p./°C (Torr)[a]	$[\alpha]_D^{20}$	$[\alpha]_D^T$ for 100% ee (T/°C)	ee (%)
4	Aldrich	40–41 (10)	+51.1 (neat)	+51.1 (20)[b] (neat)	>99
5	Aldrich	40 (10)	−51.1 (neat)	−51.3 (20)[b] (neat)	>99
6	*c*	48 (5.5)	−43.8 (neat)	−46.6 (23)[c] (neat)	94
7	*d*	60–64 (0.2)	−32.4 (neat)	−35.1 (26)[d] (neat)	92
8	Aldrich	105–110 (0.01)	−26.6 (*c* 10.0, $CHCl_3$)	−29.8 (20)[e] (*c* 10.0, $CHCl_3$)	89
9	Aldrich	83–84 (1.5)	−36.4 (neat)	−40.1 (20)[f] (neat)	91

[a] Compounds **4–8** were distilled from calcium hydride. [b] Ref. 54. [c] Ref. 14. [d] Ref. 20. [e] Ref. 17. [f] Ref. 18.

(±)-*Methyl 2-phenylpropanoate* **18**. Racemic 2-phenylpropanoic acid (Aldrich) (9.97 g, 66.4 mmol) and boron trifluoride–methanol complex (15.0 cm^3, 180.7 mmol) in methanol (70 cm^3) was heated under reflux for 8 h.[42] Methanol was then removed under reduced pressure, the residue was taken up in diethyl ether (150 cm^3) and washed with saturated aq. sodium hydrogen carbonate (4 × 100 cm^3) followed by saturated aq. sodium chloride (brine) (3 × 80 cm^3) and then dried ($MgSO_4$ + K_2CO_3). Ether was removed under reduced pressure and the residue was distilled to yield 8.3 g (76%) of **18**, b.p. 62–65 °C/2.9 Torr* (lit.,[43] b.p. 98–100 °C/12 Torr).

The racemic methyl esters **21**,[44] **23**[45] and **25**[46] were prepared by the same method from commercially-obtained acids; **24**[47] was obtained similarly by esterification of 3,3-dimethyl-2-phenylbutanoic acid.[48] The ester **22**[49] was prepared by treatment of methyl 1-naphthylacetate with lithium diisopropylamide in tetrahydrofuran, followed by quenching of the enolate with methyl iodide. Ethyl 2-phenylpropanoate[50] **19** was obtained by esterification of the acid with ethanol in the presence of concentrated sulfuric acid.

(±)-tert-*Butyl 2-phenylpropanoate* **20**. B.p. 60–64 °C/0.02 Torr. Ester **20** was prepared by treatment of 2-phenylpropanoyl chloride[35] with *tert*-butyl alcohol in the presence of triethylamine, using diethyl ether as solvent (Found: C, 75.9; H, 8.8. $C_{13}H_{18}O_2$ requires C, 75.7; H, 8.8%).

Authentic samples of optically active esters were prepared from (*R*)-(−)-2-phenylpropanoic (Aldrich), (*R*)-(−)-2-phenylbutanoic (Aldrich) and (*S*)-(+)-3-phenylbutanoic (Fluka) acids; (*R*)-(−)-2-(4-isobutylphenyl)propanoic acid was a gift from Dr J. W. Cooper. The methyl 2-phenylpropanoate so prepared contained a 94% ee of the (*R*)-enantiomer.

Racemic dimethyl 2,2-dimethyl-1,3-dioxolane-*trans*-4,5-dicarboxylate was prepared from racemic tartaric acid using the method of Carmack and Kelley.[51] The (4*S*,5*S*) enantiomer **26** and its antipode were obtained from Fluka Chemicals; both were enantiomerically pure, as judged by ^1H NMR spectroscopy in the presence of Eu(hfc)$_3$.

(1*R*)-(+)- and (1*S*)-(−)-camphor (Aldrich) were used as received. Racemic camphor (Aldrich, lot no. 35216) was purified by sublimation at 0.15 Torr (bath temp. 50 °C); it showed $[\alpha]_D^{20}$ +0.95 (*c* 11.0, 95% EtOH) corresponding[30] to an ee of 2.2% in favour of the (1*R*)-(+)-enantiomer. Conversion to the 2,4-dinitrophenylhydrazones,[52] as described below, and analysis by chiral-stationary-phase HPLC showed the sample to contain a 2.4% ee of (1*R*)-(+)-camphor. Synthetic camphor from another commercial source (Lancaster Synthesis, lot no. 3224) also proved not to be totally racemic [1.2% ee of (1*S*)-(−)-camphor].

Catalyst Preparation.—Trimethylamine–butylborane was prepared by the method of Hawthorne.[53] The amine–boranes ^{d}IpcT[10–13] (m.p. 120–145 °C dec., lit.,[10–13] m.p. 140–141 °C) and ^{l}EapT[14] (m.p. 123–140 °C., lit.,[14] m.p. 138–141 °C) were prepared as described in the literature, from the pinenes listed in Table 3; both complexes were presumed to be enantiomerically pure. The complex ^{l}IpcT was prepared from (1*S*)-(−)-α-pinene in the same way as its antipode.

N,N′-*Bis*[(1S,2R,3S,5S)-*iso*-2-(2-*methoxyethyl*)*apopinocampheylborane*]-*TMEDA Complex* (^{l}*MeapT*).—A solution of BMS (2.6 cm^3, 26.0 mmol) in diethyl ether (15 cm^3) was heated to reflux and nopol methyl ether **7** (9.80 g, 54.4 mmol) was added dropwise with stirring. After the addition, the mixture was heated under reflux for 4 h, TMEDA (2.0 cm^3, 13.3 mmol) was added and the reflux was continued for a further 1 h. The solution was allowed to cool to room temp. and most of the volatiles were removed under reduced pressure, using a trap cooled to −78 °C to prevent the escape of odorous Me_2S. Hexane (15 cm^3) was added to the residue and the mixture was kept at −20 °C to induce crystallisation. The product was collected by filtration, washed with cold hexane (5 × 5 cm^3) and dried *in vacuo* (0.01 Torr) at room temp. to give 3.2 g (48%) of ^{l}MeapT, which was recrystallised from hexane–diethyl ether (2.5:1); m.p. 60–85 °C dec. (Found: C, 71.3; H, 12.4; N, 5.3. $C_{30}H_{62}B_2N_2O_2$ requires C, 71.4; H, 12.4; N, 5.6%); δ_H 0.69 (br m, 2 H, CHB), 0.78 (d, 2 H, *J* 8.8), 1.10 (s, 6 H, C*Me*^{A}Me^B), 1.16 (s, 6 H, CMe^A*Me*^{B}), 1.44 (m, 2 H), 1.69 (m, 4 H), 1.85 (m, 6 H), 2.09 (m, 2 H), 2.21 (m, 2 H), 2.58 (s, 6 H, NMe^A), 2.61 (s, 6 H, NMe^B), 3.19 (m, 4 H, CH_2N), 3.32 (s, 6 H, OMe) and 3.38 (m, 4 H, CH_2OMe).

N,N′-*Bis*[(1S,2R,3S,5S)-*iso*-2-(2-*benzyloxyethyl*)*apopinocampheylborane*]-*TMEDA Complex* (^{l}*BeapT*).—This compound was prepared in a similar way from nopol benzyl ether **8** (14.7 g, 57.5 mmol). The complex (4.3 g, 55%) was recrystallised from hexane–diethyl ether (1:1); m.p. 80–89 °C dec. (Found: C, 76.8; H, 10.7; N, 4.3. $C_{42}H_{70}B_2N_2O_2$ requires C, 76.8; H, 10.7; N, 4.3%); δ_H 0.68 (br m, 2 H, CHB), 0.78 (d, 2 H, *J* 8.8), 1.10 (s, 6 H, C*Me*^{A}Me^B), 1.15 (s, 6 H, CMe^A*Me*^{B}), 1.46 (m, 2 H), 1.7–1.9 (m, 10 H), 2.09 (m, 2 H), 2.20 (m, 2 H), 2.57 (s, 6 H, NMe^A), 2.58 (s, 6 H, NMe^B), 3.18 (m, 4 H, CH_2N), 3.47 (m, 4 H, OCH_2CH_2), 4.47, 4.52 (AB quart, 4 H, J_{AB} 12.0, PhCH_2) and 7.2–7.4 (m, 10 H, Ph).

Enantiomeric Compositions of ^{l}*MeapT and* ^{l}*BeapT*.—The procedure used was the same for both complexes and is given

* 1 Torr ≈ 133 Pa.

for ^{l}MeapT. A solution of BMS (6.5 cm^3, 65 mmol) in diethyl ether (30 cm^3) was heated to reflux and nopol methyl ether **7** (11.37 g, 63.1 mmol) was added dropwise during 20 min. After the addition, the mixture was heated under reflux for a further 4 h, allowed to cool to room temp. and ethanol (30 cm^3) was added dropwise. The solution was stirred until no more hydrogen was evolved, then aq. sodium hydroxide (3.0 mol dm^{-3}; 22.0 cm^3, 66 mmol) was added and the mixture was cooled in an ice–water bath before dropwise addition of aq. hydrogen peroxide (30% w/v; 7.6 cm^3, 67 mmol). Following addition of the peroxide, the mixture was stirred and heated on a water bath at 60 °C for 1.25 h, allowed to cool to room temp. and poured into ice–water (250 cm^3). More ether (100 cm^3) was added and the organic layer was separated and washed with water (2 × 50 cm^3), brine (50 cm^3) and dried (K_2CO_3). After removal of the ether, the residual oil was distilled to give 8.1 g (68%) of iso-2-(2-methoxyethyl)apopinocampheol,[20] b.p. 84–86 °C/0.45 Torr; δ_H 0.91 (s, 3 H, C*Me*^{A}Me^B), 1.08 (d, 1 H, *J* 9.6), 1.21 (s, 3 H, CMe^A*Me*^{B}), 1.59 (m, 1 H), 1.76 (m, 1 H), 1.81–1.97 (m, 4 H), 2.36 (m, 1 H), 2.47 (m, 1 H), 3.31 (s, 1 H, OH), 3.38 (s, 3 H, OMe), 3.44–3.61 (m, 2 H, C*H*$_2$OMe) and 4.15 (m, 1 H, *H*COH).

The Mosher ester[26] was prepared according to the method of Ward and Rhee.[27] Oxalyl chloride (50 mm^3, 0.573 mmol) was added to a solution of (*R*)-(+)-Mosher's acid (0.025 g, 0.107 mmol) and *N*,*N*-dimethylformamide (9.5 mm^3, 0.123 mmol) in hexane (5 cm^3) at room temp. under argon and the mixture was stirred for 1 h. The liquid was decanted into another flask and the hexane was removed under reduced pressure. A solution of iso-2-(2-methoxyethyl)apopinocampheol (0.0132 g, 0.067 mmol), triethylamine (40 mm^3, 0.287 mmol) and 4-dimethylaminopyridine (0.0121 g, 0.099 mmol) in $CDCl_3$ (1 cm^3) was added to the residue. This was left to stand at room temp. for 1.5 h, after which NMR spectroscopic examination showed complete conversion into the diastereoisomeric Mosher esters **16**. The NMR peaks arising from the 3-H and from the CF_3 group were used to determine the diastereoisomeric composition. The major diastereoisomer (96%) showed δ_H 5.23 (dt, 1 H, *J* 9.5, 4.1) and δ_F 4.17 (s); the minor diastereoisomer (4%) showed δ_H 5.29 (dt, 1 H, *J* 9.5, 4.0) and δ_F 4.22 (s), confirming that the ee of the starting nopol methyl ether **7** was 92 ± 1% (see Table 3).

Ethanol (5 cm^3) was added dropwise to a stirred solution of ^{l}MeapT (0.549 g, 1.09 mmol) in diethyl ether (5 cm^3), followed by aq. sodium hydroxide (3.0 mol dm^{-3}; 0.8 cm^3, 2.4 mmol). The mixture was then cooled in an ice bath and aq. hydrogen peroxide (30% w/v; 0.4 cm^3, 3.5 mmol) was added dropwise. The mixture was heated on a water bath at 60 °C for 1.25 h, allowed to cool to room temp. and poured into ice–water (10 cm^3). More ether (15 cm^3) was added and the organic layer was separated and washed successively with water (2 × 10 cm^3), dilute sulfuric acid (0.2 mol dm^{-3}; 10 cm^3), aq. sodium hydrogen carbonate (10 cm^3) and with brine (10 cm^3) and then dried (K_2CO_3). After removal of the solvent, the residue was subjected to column chromatography, using hexane–ethyl acetate (7:3) as eluent, to give 0.32 g (74%) of iso-2-(2-methoxyethyl)apopinocampheol. The alcohol was esterified as before and the diastereoisomeric composition of the Mosher ester **16** was determined by $^1H/^{19}F$ NMR spectroscopy, showing that the ee of the ^{l}MeapT was 91%.

Nopol benzyl ether **8** was hydroborated and oxidised to give iso-2-(2-benzyloxyethyl)apopinocampheol[25] by the method used for **7**; b.p. 120–121 °C/0.01 Torr; δ_H 0.90 (s, 3 H, C*Me*^{A}Me^B), 1.07 (d, 1 H, *J* 10.0), 1.21 (s, 3 H, CMe^A*Me*^{B}), 1.62 (m, 1 H), 1.74 (m, 1 H), 1.78–1.99 (m, 4 H), 2.35 (m, 1 H), 2.46 (m, 1 H), 3.15 (d, 1 H, *J* 2.8, OH), 3.54–3.72 (m, 2 H, OC*H*$_2$CH$_2$), 4.16 (m, 1 H, *H*COH), 4.53 (s, 2 H, C*H*$_2$Ph), 7.25–7.40 (m, 5 H, Ph). The alcohol was esterified with Mosher's acid chloride as before and again the NMR signals arising from 3-H and from the CF_3 group were used to determine the diastereoisomeric composition of the ester **17**. The major diastereoisomer (95%) showed δ_H 5.20 (dt, 1 H, *J* 9.8, 4.2) and δ_F 4.02 (s); the minor diastereoisomer (5%) showed δ_H 5.35 (dt, 1 H, *J* 9.7, 4.2) and δ_F 4.10 (s), confirming that the ee of the starting nopol benzyl ether **8** was 90 ± 1%.

Oxidation of ^{l}BeapT with alkaline hydrogen peroxide as before gave iso-2-(2-benzyloxyethyl)apopinocampheol, which was purified by column chromatography, using hexane–ethyl acetate as eluent (7:3), and then esterified to give the Mosher ester **17** which showed the ee of the ^{l}BeapT to be ≥98.5%.

UV Irradiation.—Two experimental arrangements were used; all sample tubes and other apparatus through which the photolysing beam passed were made from fused silica.

For reactions at *ca.* −73 °C (solid CO_2–ethanol coolant), a water-cooled 150 W medium-pressure mercury discharge lamp (Heraeus) was positioned against the outer wall of an unsilvered dewar flask, using thin cork spacers to prevent actual contact. The dewar was backed with aluminium foil to act as a reflector. The sample tube was suspended inside a guide tube, which was perforated to facilitate circulation of cold ethanol (transparent in the near-UV), but which prevented pieces of solid CO_2 from blocking the light path. The guide tube was fixed, using silicone rubber cement, close up against the inside wall of the dewar. A rubber O-ring was pushed onto the sample tube to allow alignment with the discharge tube, which was *ca.* 5 cm away. The sample was removed and mixed by shaking at frequent intervals. The temperature of the reaction mixture during photolysis was estimated in a separate experiment, by immersing a thermocouple in a solution of DTBP in diethyl ether contained in an open sample tube. A current of warm air was blown intermittently onto the outside of the dewar to prevent condensation of moisture in the region of photolysis and the whole apparatus was contained in a ventilated metal cupboard.

Reactions were also carried out at a more easily-adjustable temperature using the dewar cavity insert from a Varian temperature control unit designed for operation with an EPR spectrometer. The upper part of the standard insert was cut off and replaced with a wide-bore section which could accommodate sample tubes up to 9 mm diameter. Pre-cooled nitrogen was passed through the dewar insert and around the sample to control its temperature, which was monitored by a thermocouple placed alongside the sample tube. The section of the insert which contained the sample was surrounded by a fused silica tube sealed to the insert with silicone rubber. Through the jacket so formed, which was backed with aluminium foil to act as a reflector, a slow flow of dry argon was maintained to prevent condensation of moisture on the insert. Unfiltered light from a Mazda 250 W high-pressure mercury arc lamp was focussed onto the sample using two lenses of focal length 10 cm (10 cm diameter). The sample temperature during photolysis was estimated in a separate experiment, by immersing a small thermocouple in an open sample tube containing a solution of DTBP in diethyl ether and relating the temperature of this to the reading obtained from the external thermocouple positioned in the gas flow. Quoted reaction temperatures are considered accurate to ± 5 °C. The lamp could be shuttered to facilitate removal of the sample, which was mixed by shaking at frequent intervals.

Typical Procedure for Kinetic Resolution.—(a) *Methyl 2-phenylpropanoate* **18**. The complex ^{d}IpcT (0.063 g, 0.15 mmol) was transferred to a dry, argon-filled quartz sample tube (9 mm o.d., 1 mm wall). A mixture of racemic methyl 2-phenylpropanoate (250 mm^3), DTBP (560 mm^3) and *tert*-butyl-

benzene (160 mm^3) was prepared and a portion of this (485 mm^3) was transferred to the sample tube, which was then attached to the vacuum line and the contents were frozen in liquid nitrogen. The tube was evacuated and oxirane (520 mm^3) was condensed onto the frozen reagents before the tube was flame-sealed under vacuum. The sample was transferred to a solid CO_2–ethanol bath and the contents were mixed thoroughly by repeated inversion of the tube. The sample was UV irradiated for 5 h at −77 °C with light from the 250 W high-pressure mercury lamp. The tube was removed from the dewar insert every 20–30 min and the contents were mixed by shaking. The sample tube was then cooled in a solid CO_2–ethanol bath and cracked open at the neck. Toluene (2 cm^3) was added and the contents were transferred into a small round-bottomed flask which was kept in ice. The ester consumption was determined by GLC analysis of this solution, using the *tert*-butylbenzene as internal standard, by comparison with the chromatogram obtained from the stock mixture before photolysis. Volatile material was removed from the sample under reduced pressure (15 Torr) at 30 °C, the residue was dissolved in diethyl ether (30 cm^3) and the solution was washed with aq. sulfuric acid (1.8 mol dm^{-3}; 4 × 25 cm^3), followed by saturated sodium hydrogen carbonate (4 × 25 cm^3) and then dried ($MgSO_4$). Volatiles were removed at room temp./*ca.* 1.2 Torr and the residual ester was purified by column chromatography, using hexane–diethyl ether (4:1) as eluent, or by HPLC, using hexane–ethyl acetate (95:5) eluent. The ester was examined by chiral stationary phase HPLC and by ^1H NMR spectroscopy in the presence of $Eu(hfc)_3$; the ee was calculated from the relative intensities of the CH*Me* (d) signals.

The *meso*- and (±)-dehydrodimers[33-35] of **18** were isolated by preparative HPLC from the crude residual ester before column chromatography. The *meso*-dimer was obtained as a solid; δ_H 1.68 (s, 6 H, CMe), 3.74 (s, 6 H, CO_2Me) and 6.80–7.40 (m, 10 H, Ph) [lit.,[34] (CCl_4) 1.66 (s, 6 H, CMe), 3.66 (s, 6 H, CO_2Me) and 6.6–7.3 (m, 10 H, Ph)]. The (±)-dimer was isolated as a liquid; δ_H 1.78 (s, 6 H, CMe), 3.70 (s, 6 H, CO_2Me), 6.70–7.20 (m, 10 H, Ph) [lit.,[34] (CCl_4) 1.83 (s, 6 H, CMe), 3.66 (s, 6 H, CO_2Me) and 6.68–7.22 (m, 10 H, Ph)].

(b) *Camphor* **27**. The sample was prepared, as described in (*a*), from ^dIpcT (0.0625 g, 0.15 mmol), oxirane (630 mm^3) and an aliquot (370 mm^3) of a solution consisting of camphor [0.123 g, 0.80 mmol; 49.4% (1*R*)-(+) and 50.6% (1*S*)-(−)], DTBP (290 mm^3) and *tert*-butylbenzene (80 mm^3). It was sealed in a 10 mm o.d. (1 mm wall) quartz tube and irradiated for 2.5 h at *ca.* −73 °C with light from the 150 W medium pressure mercury lamp, as described above. The sample was mixed every 20–30 min by repeated inversion in a solid CO_2–ethanol bath. The sample tube was opened, the oxirane was allowed to evaporate, the residue was taken up in toluene (2 cm^3) and the solution was subjected to GLC analysis to determine the consumption of camphor.

2,4-Dinitrophenylhydrazine (0.25 g, 1.3 mmol) was suspended in ethanol (5 cm^3) and sufficient concentrated sulfuric acid (*ca.* 0.3 cm^3) was added to give a homogeneous solution, which was then added to the toluene solution. The mixture was heated for 10 min at 50 °C, most of the solvents were removed under reduced pressure (15 Torr) at room temp. and the remaining solution was subjected to column chromatography (hexane–ethyl acetate 17:3 v/v) to yield the DNP derivative of camphor. Care was taken at all stages to ensure that no resolution of the sample could take place by fractional crystallisation of the DNP derivative, which was kept in homogeneous solution at all times. The enantiomeric composition of the DNP derivative was determined by HPLC using a Chiralcel OD column (hexane–isopropyl alcohol 99:1 v/v). The same ee was found if the DNP derivative was additionally purified by achiral-phase HPLC before the enantiomeric composition was determined.

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