Asymmetric Reaction of (*RS*)-2-Phenylpropanal with Chiral Aluminium Alkoxides. Part 1

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The reaction of chiral aluminium alkoxides (2) [(−)-menthyloxide (2a); (−)-2-methylbutoxide (2b); (−)-2-butoxide (2c); and (−)-2-bornanyl oxide (2d)] with (*RS*)-2-phenylpropanal (1) gives the optically active (*S*)-(−)-2-phenylpropyl (*R*)-(−)2-phenylpropanoate (3), and the mixed esters (−)-menthyl 2-phenylpropanoate (5a), (+)-2-phenylpropyl 2-methylbutanoate (4b), and (+)-2-methylbutyl 2-phenylpropanoate (5b), respectively. An asymmetric disproportionation reaction mechanism has been proposed for compound (1).

ALTHOUGH many papers have dealt with asymmetric reduction of prochiral carbonyl compounds,[1–6] there are only a few known examples of asymmetric reduction with chiral alkoxides. The Meerwein–Ponndorf–Verley (M–P–V) reduction of prochiral ketones using chiral aluminium alkoxides is an important example. However, the stereoselectivity achieved is frequently very low,[7,8] and this may be due to the equilibrium nature of the reaction which leads to extensive racemisation of the product *via* re-oxidation of the initially-formed alcohol.

Until now, however, there has been no information about the effect of chiral aluminium alkoxides on the course of the Tischenko reaction involving racemic mixtures of aldehydes with an asymmetric carbon α to the aldehyde group. Before starting the present study we hoped that the asymmetric character of the disproportionation reaction, leading to the formation of the optically active ester, would enable us to elucidate the mechanism of certain stages of the Tischenko reaction. The mechanism of the Tischenko reaction has been of interest for some time,[9–12] and several alternatives have been proposed.

In the mechanism proposed by Lin and Day [10] it is assumed that a complex compound is formed as a result of the co-ordination of the aldehyde by the aluminium alkoxide. Another aldehyde molecule is then thought to combine with that complex compound, followed by an intramolecular hydride ion-transfer process, whereupon the said complex compound decomposes into an ester and an aluminium alkoxide.

Ogata and Kawasaki proposed another reaction mechanism whereby the formation of a complex compound of aluminium alkoxide with the aldehyde is also assumed.[12] In their mechanism, however, the alkoxide ion at the aluminium atom is transferred to the carbonyl group of the co-ordinated complex, a mixed aluminium alkoxide being formed. The next step involves the co-ordination of another aldehyde molecule by the aluminium alkoxide and the simultaneous hydride ion transfer, a mixed ester being thus formed.

The basic aim of this work involved the determination of the mechanism of the Tischenko reaction by means of asymmetric induction. Consequently, we attempted to study in detail the asymmetric Tischenko reaction of (*RS*)-2-phenylpropanal (1) with optically active aluminium alkoxides (2a—d).

RESULTS AND DISCUSSION

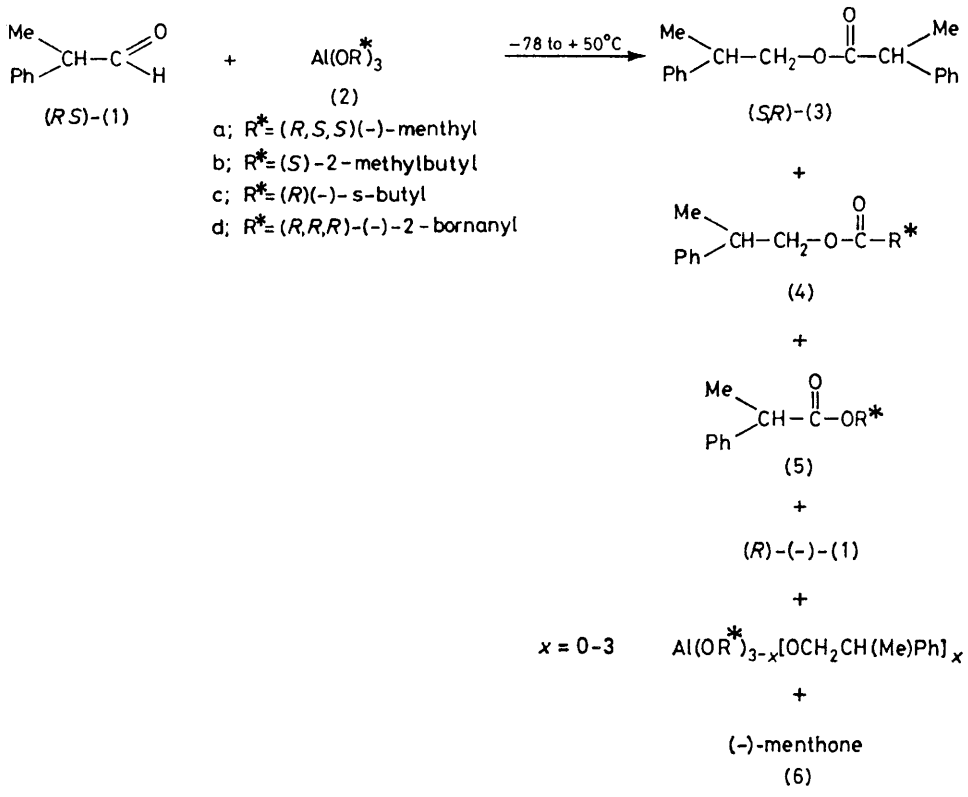
The condensation of (*RS*)-2-phenylpropanal (1) was carried out in a variety of solvents [methylene dichloride, toluene, (*S*)-(—)-2-methylbutanol, THF, diethyl ether] in the presence of chiral aluminium alkoxides in the temperature range −78—+50 °C. The catalyst concentration of aluminium (—)-menthyloxide (2a), aluminium (—)-2-methylbutoxide (2b), aluminium (—)-2-butoxide (2c), and aluminium (—)-2-bornanyl oxide (2d) was varied from 0.5 to 20 mol%.

The application of these chiral catalysts leads to the optically active diastereoisomeric ester (3), the mixed esters (4) and (5), unreacted aldehyde and (—)-menthone (6) or (—)-camphor [Scheme 1]. It is possible to isolate the reaction products by fractional distillation. The composition of the reaction products was also determined by g.l.c. Treatment of the esters with alkaline KOH at room temperature gave 2-phenylpropanol [13] and 2-phenylpropanoic acid [14,15] of known absolute configuration.

The mixed menthol ester (5a) did not undergo alkaline hydrolysis at room temperature, and was separated from the alcohol fraction by fractional distillation. The experimental results obtained show that the composition and magnitude of the optical activity of the products of the asymmetric disproportionation reaction depend on the nature and concentration of the catalyst and on the reaction temperature (see the Table).

The catalyst activity was expressed in terms of the optical activity of the diastereoisomeric esters, and the optical purity of the alcohols and acids obtained from them. The results obtained demonstrate clearly that, in comparison with other aluminium alkoxides, aluminium (—)-menthyl oxide (2a) is the most active catalyst in the Tischenko reaction of (*RS*)-(1). The disproportionation of (1) by (2a) leads mainly to the formation of the diastereoisomeric ester (—)-2-phenylpropyl-2-phenylpropanoate (3) with the (*S*,*R*)-configuration, (—)-menthone (6), and (—)-menthyl 2-phenylpropanoate (5a). At low catalyst concentration (0.5—2.0 mol%) only traces of the mixed ester (5a) were detected by g.l.c. in the reaction products. The higher concentration of

(2a) resulted in an increase in the optical yield of (*S*)-(−)-2-phenylpropanol (11) obtained from the esters (3). Higher concentrations of (2a) were also found to give appreciably higher yields of (6), the amount of the mixed ester (5a) decreasing gradually. It should be emphasized that the Tischenko reaction was shown to exhibit its asymmetric nature even in the case when the same aluminium alkoxide catalyst was used in successive experiments with the aldehydes. However, the chemical composition and optical activity of the catalyst was found to change in each successive synthesis. Thus in the reaction, of *e.g.* (1) with (2a), all the menthyloxy-groups of the catalyst were replaced with 2-phenylpropoxy-groups, the catalyst optical activity changing simultaneously from $[\alpha]_{546}^{20}$ −136.1° to $[\alpha]_{546}^{20}$ +7.41° (*c* 2.0, benzene) (Scheme 2). Application of the catalyst (2a′–2a″) [*i.e.* after two successive syntheses with the aldehyde (1)] for the reaction with another aldehyde 3,4-dihydro-2,5-dimethyl-2*H*-pyran-2-carbaldehyde (the dimer of methacrylaldehyde) (7) was shown to lead to the formation of mainly the mixed ester (8) and the simple ester (3).



Scheme 1

This result is thought to indicate that the alkoxy-groups in the catalyst are replaced continuously with the alkoxy-groups derived from the corresponding reduced aldehydes. This process is accompanied by the simultaneous oxidation of the corresponding alcohols to the aldehyde (1) and the formation of the simple ester (3). That free aldehydes do indeed participate in the asymmetric Tischenko reaction is supported by results of experiment (10) carried out using aldehyde (1) and catalyst (2a) in (*S*)-(−)-2-methylbutanol. The following optically active esters were the products of the reaction: optically active simple esters of (3), $[\alpha]_{546}^{20}$ −10.95° (neat); (*S*)-(−)-2-methylbutyl(*S*)-(+)-2-methylbutanoate (13), $[\alpha]_{546}^{20}$ + 5.8° (neat); and the mixed esters (+)-2-phenylpropyl 2-methylbutanoate (4b), (−)-2-methylbutyl 2-phenylpropanoate (5b), $[\alpha]_{546}^{20}$ −0.76° (neat), and (5a), $[\alpha]_{546}^{20}$ −64.98° (neat). The formation of the mixed ester (4b) in the reaction may be explained by the oxidation of the (*S*)-(−)-2-methylbutanol to the aldehyde (15), which then undergoes disproportionation. Our investigations on the asymmetric Tischenko reaction mechanism were then extended to include other chiral aluminium alkoxides.

The reaction of (1) catalysed by 20 mol% aluminium (−)-2-methylbutoxide (2b) was shown to result in the formation of small amounts of simple esters; (13), 4%, $[\alpha]_{546}^{20}$ +5.6° (neat), and (3), 18.7%, $[\alpha]_{546}^{20}$ −0.75° (neat), and a mixture of mixed esters: (*S*,*R*)-(5b), 59.2%, $[\alpha]_{546}^{20}$ +3.8° (neat), and (*S*,*S*)-(4b), 24.6%, $[\alpha]_{546}^{20}$ +2.54° (neat). After the reaction products had been distilled off, the same catalyst [*i.e.* (2b)] was used for the next reaction with (*R*,*S*)-(1). Reaction products having a different composition were obtained; *i.e.* the simple ester (3), yield 72%, $[\alpha]_{546}^{20}$ −0.15° (neat), and the mixed esters (4b) and (5b), yields 24 and 4.0%, respectively, $[\alpha]_{546}^{20}$ +4.73° (neat).

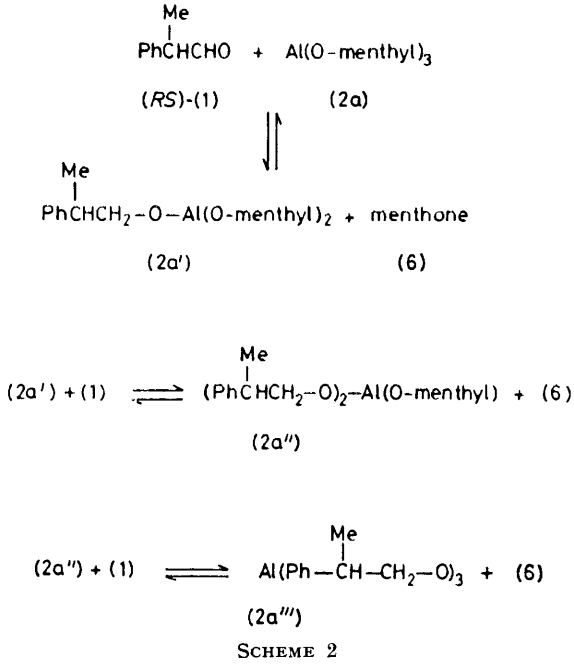
The changed yields of the esters (4b) and (5b) (24 and 4%) are thought to be due to the altered quantitative

TABLE

	(*RS*)-Aldehyde [mol l^{-1}]	Chiral Al(OR*)$_3$ [mol %]	Time (t/h)	Temp. (°C)	Solvent	Products: Unreacted aldehyde $[\alpha]_{546}^{20}$	Unreacted aldehyde Yield (%)	(−)-Camphor $[\alpha]_{546}^{20}$	(−)-Camphor Yield (%)	(−)-Menthone $[\alpha]_{546}^{20}$	(−)-Menthone Yield [a] (%)	Esters: Mixed $[\alpha]_{546}^{20}$	Mixed Yield (%)	Mixed Esters	Simple $[\alpha]_{546}^{20}$	Simple Yield (%)	Simple Ester	Hydrolysis products (3): Alcohol (11) $[\alpha]_{546}^{20}$	Alcohol (11) e.e.	Alcohol (11) Chirality	Acid (12) $[\alpha]_{546}^{20}$	Acid (12) e.e.	Acid (12) Chirality
1	(1) [1.22]	(2a) [17.5]	4	−78	CH_2Cl_2					−22.8	58.0	−68.4	9.8	(5a)	−11.8 −6.7	46.0 44.0	(3)	−8.1 −4.2	38.6 20.0	*S* *S*	−2.5 −1.8	2.27 1.64	*R*
2	(1) [1.22]	(2a″–2a‴)	24	−78	CH_2Cl_2	−0.72	16.0						0.5	(5a)	+1.2 −1.15	49.0 35.0	(3)	+3.2 −0.89	15.2 4.2	*R* *S*	−1.57 −0.15	1.47 0.14	*R* *R*
3	(1) [1.22]	(2a) [17.5]	24	−78	CH_2Cl_2							−19.2	63.0	(8)	−1.02	25.0	(3)						
4	(1) [1.22]	(2a) [17.5]	4	−30	CH_2Cl_2					−24.5	67.0	−64.8	7.6	(5a)	−9.8 −5.8	31.0 60.5	(3)	−6.78 −3.2	32.2 15.2	*S* *S*	−1.3 −0.18	1.18 0.16	*R* *S*
5	(1) [1.22]	(2a) [17.5]	4	+25	CH_2Cl_2	−4.5	22.0			−28.6	62.0	−63.1	6.0	(5a)	−4.5 −1.9	25.0 57.0	(3)	−2.8 −1.0	13.3 4.7	*S* *S*	−0.51 −0.15	0.46 0.14	*R* *R*
6	(1) [1.22]	(2a) [11.0]	4	−78	CH_2Cl_2					−24.1	45.7	−69.2	3.1	(5a)	−7.9 −5.1	28.1 62.6	(3)	−6.2 −4.3	29.5 20.5	*S* *S*	−0.98 −0.19	0.89 0.17	*R* *R*
7	(1) [1.22]	(2a) [0.5]	24	−78	CH_2Cl_2					GPC	25.0	GPC	2.1	(5a)	−3.2 −1.06	25.0 68.0	(3)	−2.4 −0.9	11.4 4.3	*S* *S*	−0.25 −0.1	0.23	*R* *R*
8	(1) [2.5]	(2a) [5.0]	24	−78	THF	−12.0	31.0			−26.7	67.0		1.2	(5a)	−4.8	59.0	(3)	−3.1	14.7	*S*	−0.7	0.64	*R*
9	(1) [2.5]	(2a) [5.0]	24	−78	PhMe					−26.6	41.0	−59.8	1.6	(5a)	−5.9	89.1	(3)	−3.1	15.1	*S*	−0.2	0.18	*R*
10	(1) [4.0]	(2a) [5.0]	24	−78	CH_2Cl_2–(*S*)-amyl alcohol [b]					−21.8	56.0	−0.76 −64.8	30.6 8.16	(4b) (5b) (5a)	−8.9 −3.2	21.2 59.4	(3)	−6.4 −2.3	30.5 10.95	*S* *S*	−0.8 −0.15	0.73 0.14	*R* *R*
11	(1) [4.0]	(2b) [20.0]	48	20	CH_2Cl_2							+1.89 +3.8	24.6 59.2	(4b) (5b)	−0.75 +0.11	18.7 7.5	(3)	−0.51 +0.24	2.4 1.1	*S* *S*	−0.41 −0.12	0.37 0.11	*R* *R*
12	(1) [4.0]	(2b′–2b″)	48	20	CH_2Cl_2							−1.0 −4.73	24.0 4.0	(4b) (5b)	−0.15	72.0	(3)						
13	(1) [4.0]	(2c) [0.5]	24	20	CH_2Cl_2	−0.32	27.4								0.02	71.6	(3)						
14	(1) [4.0]	(2c) [2.5]	24	−78	CH_2Cl_2	−2.4	23.0								−0.34	77.0	(3)	−0.13	0.62	*S*	−0.24	0.22	*R*
15	(1) [1.22]	(2d) [17.5]	24	−78	CH_2Cl_2	−5.4	4.0	−29.8	65.1			−21.2	8.7	(5d)	−7.56	96.0	(3)	−4.7	22.3	*S*	−1.6	1.45	*R*
16	(1) [1.22]	(2d) [5.0]	24	−78	CH_2Cl_2			−30.0	71.6			−20.3	3.2	(5d)	−6.1	98.7	(3)	−4.2	20.0	*S*	−0.9	0.82	*R*

[a] Percentage calculated with reference to the initial amount of the catalyst. [b] (*S*)-(−)-2-Methylbutanol, $[\alpha]_{546}^{20}$ − 5.35° (neat) (*c* 1.0 mol l^{-1}).

composition of the (*S*)-2-methylbutoxy-groups in the catalyst, and also to the (*S*)-2-methylbutanal (15) formed in the reaction. The alcohol is oxidized to aldehyde, which in turn undergoes disproportionation to yield mainly the mixed ester (4b). The optical activity of the simple ester (3) obtained in the reaction of (1) catalysed by (2b) is relatively small, which may be due to the alkoxy-group chiral centre being in the β-position. The stereoselectivity of the reaction (1) catalysed by (2c) is equally small.



SCHEME 2

The disproportionation of (1) catalysed by aluminium (−)-2-bornanyl oxide (2d), obtained from (−)-2-bornanol with 44% enantiomeric excess (e.e.) leads to the formation of (3) having the (*S*,*R*)-configuration; $[\alpha]_{546}^{20}$ − 7.56° (neat).

It was found that when the disproportionation reactions of aldehyde (1) catalysed by chiral aluminium alkoxides were stopped before completion, optically active (1) with the (*R*)-configuration had been formed.

All these experimental results indicate that, in the catalytic system studied, the (*S*)-enantiomer (1) is more reactive. The maximum specific rotations found for (*S*)-2-phenylpropanol (11) and (*R*)-2-phenylpropanoic acid (12) were $[\alpha]_{546}^{20}$ −8.7° (e.e. 41.4%) and $[\alpha]_{546}^{20}$ − 2.5° (e.e. 2.2%), respectively. The low optical purity of (12) is most probably due to the following two factors; partial racemization takes place during the saponification of the ester; and the small influence of the factor controlling the stereoselectivity of that stage of the disproportionation reaction in the course of which the acidic part of the ester is formed. On the other hand, the optical purity of the alcoholic part of the ester was found to be much higher, and to depend on the amount of the chiral aluminium alkoxide used. Assuming the validity of the disproportionation reaction mechanism proposed by Ogata and Kawasaki,[12] it was to be expected that the optical purity of the ester formed (and especially of its acidic part) should increase with increasing catalyst concentration, and with the increase of the amount of the mixed ester formed.

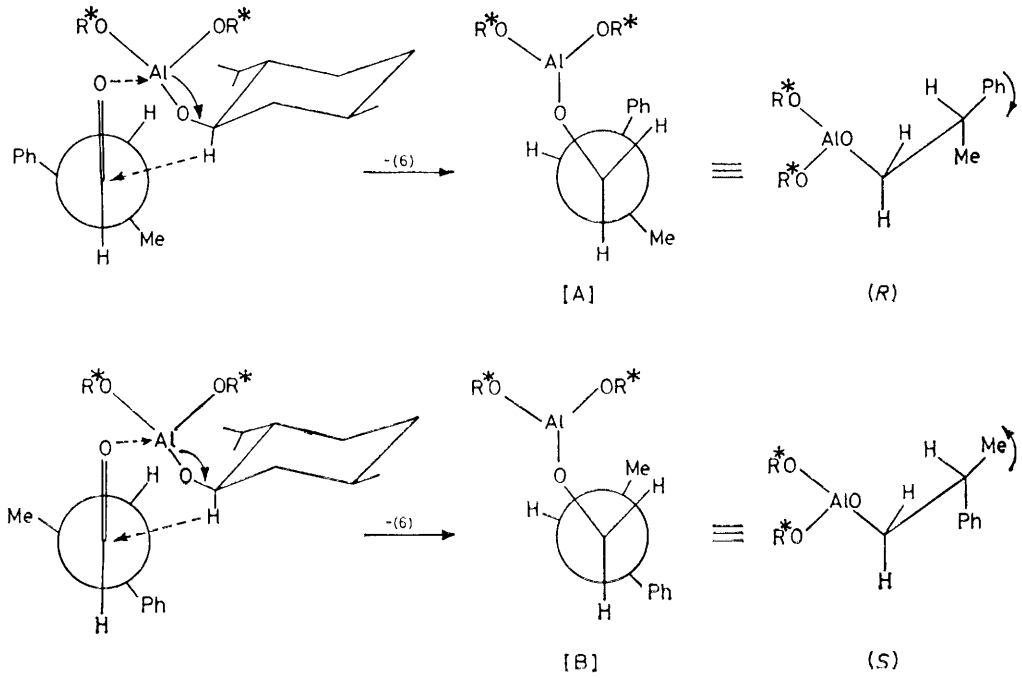
However, the considerable optical purity of the alcoholic part and the formation of mixed esters [*e.g.* (4b)], whose acidic part is derived from the alkoxy-group of the catalyst employed, cannot be explained in terms of the above-mentioned reaction mechanism, which is also unable to account for the dependence of the amount of (−)-menthone or (−)-camphor on the optical activity of the esters.

The most reasonable explanation of these results is that the first stage of the asymmetric Tischenko reaction involves the formation of a cyclic complex between the chiral aluminium alkoxide and (1). Thus the electrophilic carbon of the carbonyl group is close to the hydrogen atom in the aluminium complex, while the carbonyl oxygen is co-ordinated to the aluminium atom. According to the rules proposed by Cram [16] the favoured transition state is then the one in which each of the large (R^L) and small (R^S) substituent groups of the reagent faces similar groups (R^S and (R^L) in the substrate. From this hypothesis, two possible conformations for the transition state of cyclic complex must be then considered (Scheme 3). In our model of asymmetric induction, structures expected best to represent the two minimum-energy transition states leading to the diastereoisomers [A] and [B], were chosen. In both transition states the incoming $Al(OR^*)_2$ group is nearest to the smallest groups. The diastereoisomeric product ratio [A]/[B] was predicted from the relative magnitude of the $Al(OR^*)_2 \longleftrightarrow$ Ph[A] *vs.* $Al(OR^*)_2 \longleftrightarrow$ Me[B] interactions.

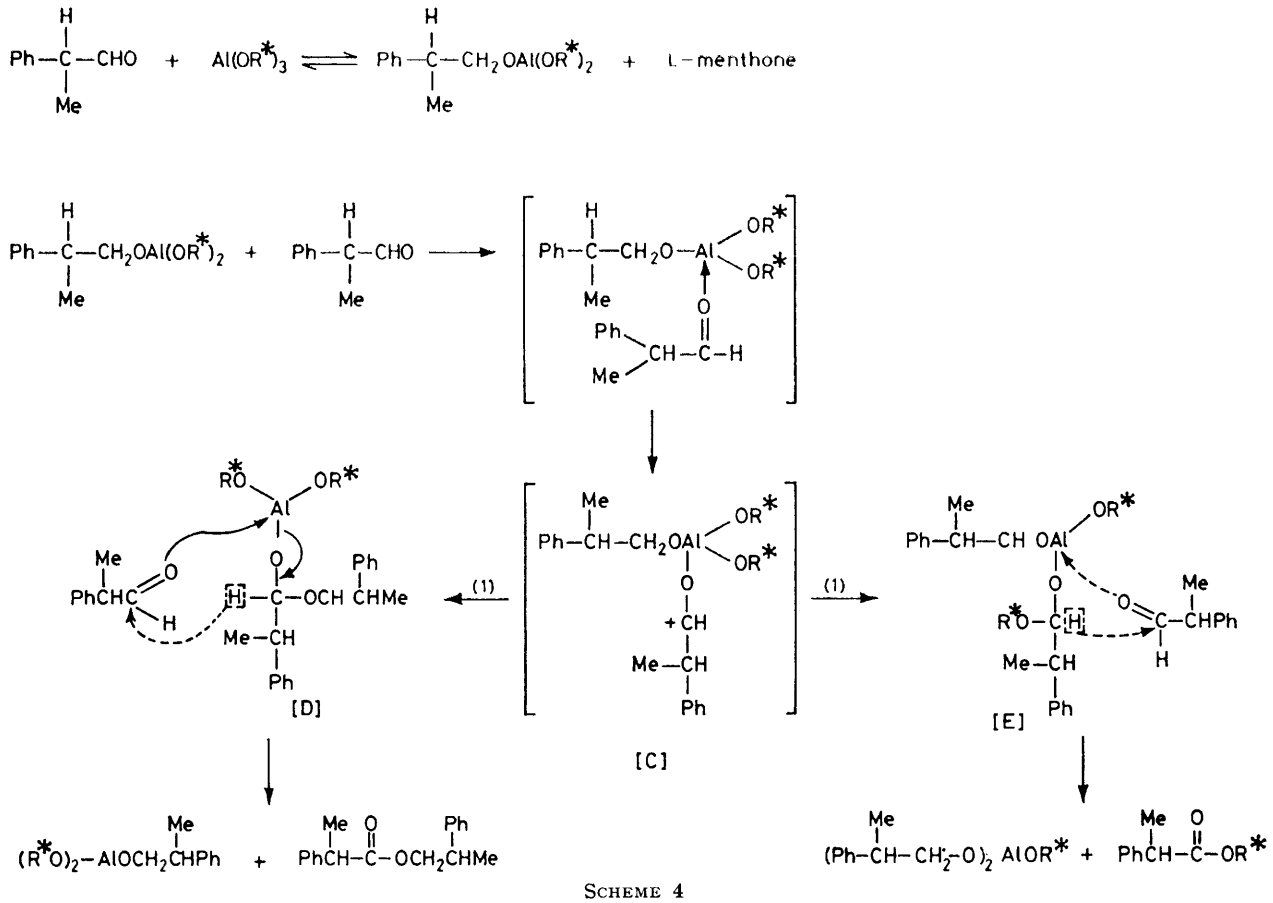
From an examination of the mode of reagent attack it follows that the preferential formation of [B] will lead to the formation of the (*S*)-enantiomer of 2-phenylpropanal. Let us now consider the steric interactions, particularly when three menthyloxy-groups are present in the catalyst. The asymmetric reduction equilibrium of (1) is favourably shifted to the right. Consequently, the first step of the asymmetric disproportionation reaction proceeds *via* hydride-ion transfer taking place under a M–P–V mechanism and the formation of a chiral mixed aluminium alkoxide (Scheme 4).

The next step most probably involves the co-ordination of the next molecule of the aldehyde to the mixed catalyst, and the subsequent formation of the intermediate compound [C]. The intermediate compound [C] can then co-ordinate the next aldehyde molecule, that process being accompanied by the transfer of the hydride ion and the alkoxy-group OR* [E] or $OCH_2CHMePh$ [D], which results in the formation of a mixed or simple ester and of a mixed aluminium alkoxide.

The stereochemical evidence presented above thus supports the view that enantioselectivity depends substantially on the steric interactions occurring between the various groups present in the aldehyde (1) and in the



SCHEME 3



SCHEME 4

aluminium alkoxide (2). A similar dependence was also observed for the asymmetric disproportionation reaction of (*R*,*S*)-2-methylbutanal and (*R*,*S*)-3,4-dihydro-2,5-dimethyl-2H-pyran-2-carboxyaldehyde. The results of these investigations will be the subject of another paper.

EXPERIMENTAL

All b.p.s were uncorrected. ^{1}H N.m.r. spectra were recorded with Varian XL-100 and JEOL 60 H instruments; i.r. spectra were recorded on a UR-20 spectrometer Carl Zeiss-Jena. Optical rotations were measured with the Polamat A Carl Zeiss-Jena polarimeter. G.l.c. was performed using a Varian 2800 instrument.

(*RS*)-2-Phenylpropanal (1) was prepared by a literature method; [15] it had b.p. 90—92 °C/10 mmHg, n_D^{20} 1.5180—1.5200.

(*RS*)-3,4-Dihydro-2,5-dimethyl-2*H*-pyran-2-carbaldehyde (7) was obtained from a Diels–Alder reaction of methacrylaldehyde,[17] b.p. 60—62 °C/15 mmHg, n_D^{20} 1.4560.

(*S*)-(−)-2-Methylbutanol, $[\alpha]_{546}^{20}$ −5.35° (neat); (*R*)-(−)-butan-2-ol, $[\alpha]_{546}^{20}$ −11.64° (neat); (−)-menthol, $[\alpha]_{546}^{20}$ −56.2° (*c* 5.0, EtOH), (−)-2-bornanol, $[\alpha]_{546}^{20}$ −23.5° (*c* 5.0, EtOH), were commercial products.

Preparation of the Optically Active Catalysts (2).—*Aluminium* (−)-*menthyl oxide* (2a). (−)-Menthol 78 g, (0.5 mol) was dissolved in dry benzene (50 ml). Activated aluminium wire (6.5 g, 0.24 mol) was added to the menthol solution and then heated for 128 h. The solvent and excess of (−)-menthol were removed by distillation in a current of dry argon at 120—125 °C/1 mmHg to give solid white product (yield 87%); $[\alpha]_{546}^{20}$ −136.1, $[\alpha]_{578}^{20}$ −120.2° (*c* 5.3, benzene). This compound was analysed for aluminium by the 8-hydroxyquinoline method (Found: Al, 5.3. Calc. for $C_{30}H_{57}AlO_3$: Al, 5.47%).

Aluminium (−)-2-*methylbutoxide* (2b). This was obtained from (*S*)-(−)-2-methylbutanol as a solid product; $[\alpha]_{546}^{20}$ −1.32, H_{578}^{20} −1.02° (*c* 20, benzene) (Found: Al, 9.1. Calc. for $C_{15}H_{33}AlO_3$: Al, 9.37%).

Aluminium S-butoxide (2c). This was obtained from (*R*)-(−)-*S*-butyl alcohol in the same manner as described above for (2a). A semi-solid product was obtained; $[\alpha]_{546}^{20}$ −3.04, $[\alpha]_{578}^{20}$ −2.76: (*c* 2.2, benzene) (Found: Al, 7.55. Calc. for $C_{12}H_{27}AlO_3$; Al, 7.79%).

Aluminium (−)-2-bornanyl oxide (2d). This was obtained from (−)-2-bornanol as a white powder, $[\alpha]_{546}^{20}$ −20.8, $[\alpha]_{578}^{20}$ −18.24° (*c* 6.2, benzene) (Found: Al, 5.2. Calc. for $C_{30}H_{54}AlO_3$: Al, 5.51%).

General Procedure for Asymmetric Reduction.—A solution of the appropriate chiral aluminium alkoxide (2) (0.5—20 mol%) was added to a stirred solution of (*RS*)-2-phenylpropanal (1) (1.22—4.0 mol l^{-1} in a solvent, see Table) at the appropriate temperature (see Table) under dry argon. The mixture was poured into water–ice and extracted with ether or chloroform. The extract was washed with 1M HCl, then 5% aqueous $NaHCO_3$, dried with $MgSO_4$, and evaporated to yield the crude reaction products, which were isolated by vacuum distillation. A g.l.c. analysis was also performed. In a repeat procedure, the apparatus was fitted for distillation with a small Vigreaux column. The mixture was distilled under high vacuum and an argon atmosphere. The residue was again treated with an appropriate amount of aldehyde (1) or (7) in solution.

The mixture of reaction products was distilled through a glass-spiral fractionating column. (−)-Menthone and (−)-camphor were converted into semicarbazones. The unreacted aldehyde (1) was reduced with sodium borohydride, and the alcohol was then purified by steam-distillation. The following optically active diastereoisomeric esters were recovered. 2-*Phenylpropyl* 2-*phenylpropanoate* (3), b.p. 156—171 °C/3 mmHg; $[\alpha]_{546}^{20}$ −11.8° (neat); n_D^{20} 1.5160; $[\alpha]_{578}^{20}$ +1.2 (neat); n_D^{20} 1.5408 (for *S*,*S*) $\nu_{max.}$ 1 730vs, 1 500s, 1 170vs, 1 208vs, 775m, and 705s cm^{-1}; $\delta(CCl_4)$ 1.05 (3 H, d, *J* 6 Hz), 1.37 (3 H, d, *J* 6 Hz), 2.9 (1 H, m) 3.1 (1 H, m), 4.0—4.2 (2 H, m), and 7.1 (10 H, m) (Found: C, 80.4; H, 7.5. $C_{18}H_{20}O_2$ requires C, 80.56; H, 7.51%).

2-*Methylbutyl* 2-*methylbutanoate* (13), b.p. 185—186 °C; n_D^{20} 1.4200—1.4269; $[\alpha]_{546}^{20}$ +5.21 to −4.07° (neat) (*S*,*S*), (*S*,*R*); $\nu_{max.}$ 1 738vs, 1 460s, 1 380s, 1 189vs, and 1 155vs cm^{-1}; $\delta(CCl_4)$ 0.9 (9 H, d), 1.05 (3 H, d), 1.2—1.8 (4 H, m), 2.0—2.1 (1 H, m), 2.2—2.5 (1 H, m), and 3.8—3.9 (2 H, m) (Found: C, 69.6; H, 11.6. $C_{10}H_{20}O_2$ requires C, 69.72; H, 11.7%). (−)-*Menthyl* 2-*phenylpropanoate* (5a), b.p. 142—133 °C/5 mmHg; n_D^{20} 1.5005; $[\alpha]_{546}^{20}$ −64.88° (neat); $\nu_{max.}$ 3 088w, 3 064w, 3 034w, 1 730vs, 1 600w, 1 500m, 1 460s, 1 375s, 1 390s, 1 210vs, 1 188vs, 765s, and 705vs cm^{-1} (Found: C, 79.0; H, 9.6. $C_{19}H_{28}O_2$ requires: C, 79.12; H, 9.78%).

(−)-2-*Bornanyl* 2-*phenylpropanoate* (5d); b.p. 136—138 °C/5 mmHg, n_D^{20} 1.5130, $[\alpha]_{546}^{20}$ −21.2° (neat); $\nu_{max.}$ 3 088w, 3 030m, 1 730vs, 1 600w, 1 500m, 1 465s, 1 375s, 1 390s, 1 240m, 1 208vs, 1 175vs, 765m, and 705s cm^{-1}; $\delta(CCl_4)$ 0.6 (3 H, s), 0.8 (3 H, s), 0.85 (3 H, s, *J* 7.5 Hz), 0.9—2.5 (7 H, m), 1.45 (3 H, d, *J* 7.5 Hz), 3.65 (1 H, q, *J* 7.5 Hz), 4.65—5.0 (1 H, m), and 7.25 (5 H, s) (Found: C, 79.6; H, 9.0. $C_{19}H_{26}O_2$ requires: C, 79.67; H, 9.15%).

(−)-3,4-Dihydro-2,2,5-*trimethyl*-2H-*pyran* 3,4-*dihydro*-2,5-*dimethyl*-2H-*pyran*-2-*carboxylate* (9), b.p. 140—142 °C/8 mmHg, n_D^{20} 1.4964, $[\alpha]_{546}^{20}$ −1.02° (neat), bromine number 112.7; $\nu_{max.}$ 3 070m, 3 025w, 1 745vs, 1 680vs, 1 450s, 1 380s, 1 175vs, 1 140vs, and 1 105s cm^{-1}; $\delta(CCl_4)$ 1.32 (3 H, d), 1.08 (3 H, s), 1.42 (6 H, s), 1.5—2.3 (8 H, m), 3.9 (2 H, m), and 5.95 (2 H, d) (Found: C, 68.4; H, 8.55; $C_{16}H_{24}O_4$ requires C, 68.54; H, 8.62%).

Mixture of (+)-2-methylbutyl 2-phenylpropanoate (4b) {b.p. 122—123 °C/5 mmHg, $[\alpha]_{546}^{20}$ +3.8° (neat), n_D^{20} 1.4876} and (+)-2-phenylpropyl 2-methylbutanoate (5b) {b.p. 107–108 °C/5 mmHg, $[\alpha]_{546}^{20}$ +1.89° (neat), n_D^{20} 1.5100}; $\nu_{max.}$ 3 090w, 3 068w, 3 035m, 1 734vs, 1 600m, 1 500m, 1 455s, 1 210vs, 1 170vs, 778s, and 705vs cm^{-1}; $\delta(CCl_4)$ (4b) −0.7 (3 H, d, *J* 6.0 Hz), 0.5—1.7 (6 H, m), 1.4 (3 H, d, *J* 6.0 Hz), 3.3—4.1 (3 H, m), and 7.1 (5 H, s); $\delta(CCl_4)$ (5b) −0.72 (3 H, d), 0.8—1.8 (5 H, m), 1.1 (3 H, d, *J* 6.0 Hz), 2.5—3.2 (1 H, m), 2.9 (1 H, m), 4.0—4.2 (2 H, m), and 7.1 (5 H, s) (Found: C, 69.6; H, 11.6. $C_{10}H_{20}O_2$ requires C, 69.72; H, 11.7%).

(−)-2-*Phenylpropyl* 3,4-*dihydro*-2,5-*dimethyl*-2H-*pyran*-2-*carboxylate* (8), b.p. 135—138 °C/5 mmHg, n_D^{20} 1.4894; $[\alpha]_{546}^{20}$ −19.2° (neat); $\nu_{max.}$ 3 069w, 3 040w, 1 745vs, 1 678vs, 1 500m, 1 455m, 1 375m, 1 290s, 1 248s, 1 190vs, 1 162vs, 1 140s, 1 020vs, 765m, and 700s cm^{-1} (Found: C, 75.1; H, 7.0. $C_{17}H_{19}O_3$ requires C, 75 25; H, 7.05%).

Hydrolysis of Esters. The ester (5 g—10 g) was stirred with alcoholic KOH solution [KOH(4—9 g) in EtOH (50 ml)] for 2 days at room temperature. The mixture was concentrated *in vacuo* to remove EtOH, diluted with water, and extracted with $CHCl_3$. The aqueous layer was acidified with ice–dilute HCl and extracted with $CHCl_3$. The $CHCl_3$ extracts were washed, dried with $MgSO_4$, and concentrated *in vacuo* to give crude alcohol and acid.

2-Phenylpropanol (11) b.p. 100—102°/10 mmHg, n_D^{20} 1.5230, $[\alpha]_{546}^{20}$ −8.1 to +3.2° (neat) [*i.e.* 38.57% e.e. (*S*) to 15 23% e.e. (*R*)]. The optical purity of (11) was estimated based on the highest reported [13] value, *i.e.* $[\alpha]_{546}^{20}$ −21.0° (neat); $\nu_{max.}$ 3 580vs, 3 560vs, 1 500s, 1 065vs, 1 020vs, 765m, and 700s cm^{-1}; $\delta(CCl_4)$: 1.2 (3 H, d, *J* 6.0 Hz), 2.75 (1 H, q), 3.48 (2 H, q), 4.08 (1 H, s), and 7.12 (5 H, s).

(*S*)-(−)-2-Methylbutanol (14), b.p. 128—129 °C, $[\alpha]_{546}^{20}$ −5.35° (neat); from mixed esters, $[\alpha]_{546}^{20}$ −4.3° (neat).

(−)-3,4-Dihydro-2,5-dimethyl-2H-pyran-2-ylmethanol (10), b.p. 96—97 °C/8 mmHg, n_D^{20} 1 4760, $[\alpha]_{546}^{20}$ −0.8° (neat) from mixed esters; $[\alpha]_{546}^{20}$ −2.46° (neat) from simple ester; bromine number 112.5; $\nu_{max.}$ 3 430vs, 3 080m, 3 020m, 1 680vs, 1 190vs, 1 160vs, and 1 145vs cm^{-1}; $\delta(CCl_4)$ 1.1 (3 H, s), 1.5 (3 H, s), 1.2—1.9 (4 H, m), 3.4 (2 H, s), 3.55 (1 H, s), and 6.0 (1 H, s).

(*R*)-(−)-2-Phenylpropanoic acid (12), b.p. 158—159 °C/25 mmHg, n_D^{20} 1.5204—1.5210, $[\alpha]_{546}^{20}$ −0.1 to −2.5° (neat); $\nu_{max.}$ 3 100—2 550vs, 1 715vs, 1 500m, 1 460s, 1 420s, 1 280vs, 1 190vs, 1 070s, 950s, 770s, 730s, and 703vs cm^{-1}; $\delta(CCl_4)$ 1.25 (3 H, d, *J* 7.5 Hz), 2.95 (1 H, q), 7.1 (5 H, m), and 12.2 (1 H, s).

(*S*)-(−)-2-Methylbutanoic acid, b.p. 177—178 °C, $[\alpha]_{546}^{20}$ +9.2—+4.6° (neat) from mixed esters (4b).

Reduction of aldehyde (1).—Sodium borohydride (1.8 g) was added to a solution of the aldehyde (1) in methanol (100 ml) with ice-cooling. The mixture was stirred for 4 h; dilute hydrochloric acid was then added and the mixture extracted with ether and the solution treated in the usual manner. The residue was distilled at 75—78 °C/5 mmHg to give (*R*)-(−)-2-phenylpropanol, $[\alpha]_{546}^{20}$ +0.5—+2.7° (neat), 89.5% yield.

Oxidation of (1).—The unreacted mixture of (1) and potassium permanganate was stirred at room temperature. The mixture was then brought to pH 7; MnO_2 was filtered off and the filtrate acidified and extracted with $CHCl_3$. The chloroform extracts were washed, dried with $MgSO_4$, and concentrated *in vacuo* to give crude (12). The acid residue was distilled to give (*R*)-(−)-2-phenylpropanoic acid (12), with $[\alpha]_{546}^{20}$ −1.7 to −7.5° (neat).

(−)*Menthone* (6).—This was obtained as the product of the Tischenko reaction catalysed by (2a); b.p. 86—88 °C/15 mmHg, $[\alpha]_{546}^{20}$ −28.7° (neat); the semicarbazone had m.p. 163—164 °C, $[\alpha]_{546}^{20}$ −45.8° (*c* 2.0, AcOH).

(−)-Camphor (15) —This was isolated from the reaction [catalysed by (2d)] mixture, m.p. 176—178 °C, $[\alpha]_{546}^{20}$ −30.06° (*c* 1.5, EtOH); the oxime had m.p. 118—119 °C.

Purification of (1) via *the* 2,4-*Dinitrophenylhydrazone*.—The aldehyde (1) was converted into its 2,4-dinitrophenylhydrazone by the usual method. This was then converted back into aldehyde (1) by mildly alkaline hydrolysis; the 2,4-dinitrophenylhydrazone of (1) (3 g) and $KHCO_3$ (7.5 g) in water–ethylene glycol (75 ml) were refluxed to give a product (1), which was of 98% purity after two steam-distillations.

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REFERENCES

[1] S. R. Landor and A. R. Tatchell, *J. Chem. Soc. C*, 1966, 2280.
[2] S. R. Landor, B. J. Miller, and A. R. Tatchell, *J. Chem. Soc. C*, 1967, 197.
[3] O. Cervinka, V. Suchan, O. Kotynek, and V. Dudek, *Collect. Czech. Chem. Commun.*, 1965, **30**, 2484.
[4] J. S. Birtwistle, K. Lee, J. D. Morrison, and H. S. Mosher, *J. Org. Chem.*, 1964, **29**, 37.
[5] Ch. Zioudru, I. Moustakali-Mavridis, and P. Chrysochon, *Tetrahedron*, 1978, **34**, 3181.
[6] J. D. Morrison and H. S. Mosher, 'Asymmetric Organic Reactions,' Prentice-Hall, Englewood Cliffs, New Jersey, U.S.A., 1971.
[7] W. von E. Döring and R. W. Young, *J. Am. Chem. Soc.*, 1950, **72**, 631.
[8] L. M. Jackman, J. A. Mills, and J. S. Shannon, *J. Am. Chem. Soc.*, 1950, **72**, 4184.
[9] V. E. Tischenko, *J. Russ. Phys. Chem. Soc.*, 1906, **38**, 355, 482.
[10] J. Lin and A. R. Day, *J. Am. Chem. Soc.*, 1952, **74**, 5133.
[11] G. Darzens, and M. Mayer, *C.R. Acad. Sci.*, 1953, **236**, 1496.
[12] T. Ogata, A. Kawasaki, and I. Kishi, *Tetrahedron*, 1967, **23**, 825.
[13] S. P. Bakshi and E. E. Turner, *J. Chem. Soc.*, 1961, 171.
[14] R. Clark and H. S. Mosher, *J. Org. Chem.*, 1970, **35**, 1114.
[15] A. I. Vogel, 'Practical Organic Chemistry,' Longmans, London, 1962, p. 906.
[16] D. J. Cram and F. A. A. Elhafez, *J. Am. Chem. Soc.*, 1952, **74**, 5828.
[17] C. W. Smith, D. G. Norton, and S. A. Ballard, *J. Am. Chem. Soc.*, 1951, **73**, 5267.