Aldehyde addition to allylic stannanes *via* a transmetallation pathway: stereocontrol in the absence of internal coordination

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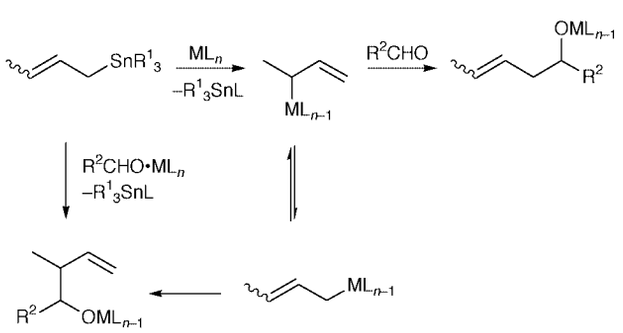
Methyltin trichloride and indium(III) chloride promote the addition of aldehydes to cyclic allylic stannanes providing good yields of the corresponding homoallylic alcohols. These reactions proceed *via* an initial transmetallation involving *anti* approach of the electrophile, followed by *syn* aldehyde addition that is *erythro* selective. These Lewis acids do not promote the corresponding addition of imines, rather providing the same homoallylic alcohols after an *in situ* aqueous hydrolysis. Imine addition is possible with boron trifluoride–diethyl ether as the Lewis acid.

Introduction

The Lewis acid promoted addition of aldehydes to allylic stannanes may proceed (i) *via* direct addition of the Lewis acid–aldehyde complex to the allylic stannane or (ii) *via* an initial transmetallation to yield a new, reactive allylic metal intermediate which subsequently reacts with the aldehyde (Scheme 1).[1] These possible reaction pathways will determine



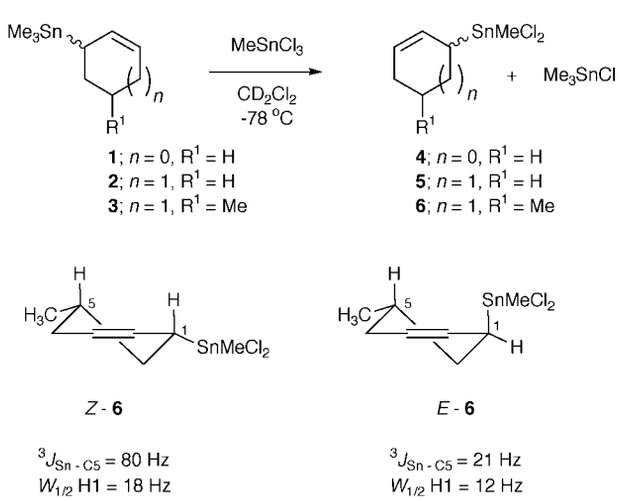
Scheme 1

the regio- and stereochemistry of the resulting homoallylic alcohol but can be difficult to control, depending on the Lewis acid, the aldehyde, the order of reagent addition and the reaction conditions.

There have been numerous reports of the transmetallation pathway, particularly involving reactions of tin halide Lewis acids.[1b,2] Common to these investigations are the observations that (i) electrophilic attack by the metal halide occurs exclusively at the γ position of the allylic triad, and (ii) the intermediate allylic metal halide is prone to metallotropic rearrangement. Control of allylic regiochemistry and high levels of asymmetric induction are possible with substrates containing an oxygen or nitrogen positioned on or near the allylic moiety.[1b,2] This functionality coordinates to the metal centre, preventing allylic isomerisation and additional coordination to the aldehyde facilitates a regio- and stereo-controlled, metallo–ene addition. We have previously communicated results concerning the stereochemistry of transmetallation between the Lewis acid CH_3SnCl_3 and cyclic allylic stannanes.[3] We now report on the general stereoelectronic and steric factors which influence aldehyde addition to cyclic allylic stannanes *via* a prior transmetallation and in the absence of coordinating functionality.

Results

Cyclic allylic stannanes **1**–**3** undergo a clean transmetallation reaction with CH_3SnCl_3 in chloroform or dichloromethane to provide the corresponding dichloromethyl allylic stannanes **4**–**6** respectively and trimethyltin chloride (Scheme 2). The



Scheme 2

stereochemistry of this process was investigated using different isomeric ratios of 5-methylcyclohex-2-enyltrimethylstannane **3**.

The relative configuration of the transmetallation product **6** was determined from the vicinal ^{119}Sn–^{13}C coupling constant and the linewidth of the C_1HSn proton NMR signal.[4] The *Z* isomer has a greater dihedral angle and so a larger vicinal coupling than the *E* isomer (Scheme 2). The C_1HSn proton of this isomer is *quasi*-axial and is, therefore, broader than that of the *E* isomer. Confirmation of these assignments was obtained by conversion of **6** back into **3** with methyllithium. These transmetallation reactions were rapid in CD_2Cl_2 at −78 °C and proceeded with stereospecific inversion of configuration (Table 1). In $CDCl_3$ at room temperature the reactions were exothermic and yielded the same product but with diminished selectivity. Upon standing (7 days, *ca.* 25 °C), reactions corresponding to entries 2 and 4 underwent isomerisation to the *E* isomer (*Z* : *E* = 27 : 73 in both cases). This was accompanied by a small amount of precipitate suggesting slight decomposition of the sample. A partial reaction at low temperature indicated that

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Table 1 Stereochemistry of transmetallation

Entry	(*E*)-**3** (%)[a]	(*Z*)-**3** (%)[a]	Solvent	Temp./°C	(*E*)-**6** (%)[a]	(*Z*)-**6** (%)[a]
1	68	32	CD_2Cl_2	−78	29	71
2	44	56	CD_2Cl_2	−78	57	43
3	60	40	$CDCl_3$	25	29	71
4	31	69	$CDCl_3$	25	51	49

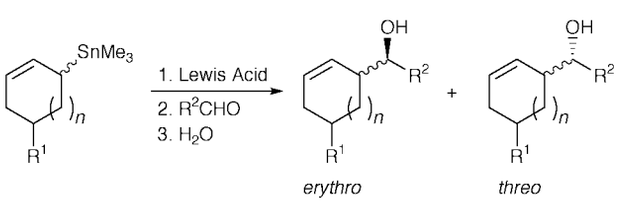
[a] Determined by ^1H and ^{13}C NMR spectroscopy.

Table 2 Stereochemistry of aldehyde addition

Entry	Stannane	(*E*):(*Z*)	R′CHO	Lewis acid	Solvent, *T*/°C	Yield (%)	Alcohol	*erythro*:*threo*	(*E*):(*Z*)
1	**1**		Ph	CH_3SnCl_3	CH_2Cl_2, 25	85	**7a**	94:6	
2	**1**		C_6H_{11}	CH_3SnCl_3	CH_2Cl_2, 25	83	**7b**	59:41	
3	**1**		Bn	CH_3SnCl_3	CH_2Cl_2, 25	83	**7c**	56:44	
4	**1**		i-Pr	CH_3SnCl_3	CH_2Cl_2, 25	80	**7d**	55:45	
5	**1**		Ph	$InCl_3$	Acetone, −78	87	**7a**	87:13	
6	**1**		C_6H_{11}	$InCl_3$	Acetone, −78	85	**7b**	87:13	
7	**1**		Bn	$InCl_3$	Acetone, −78	82	**7c**	75:25	
8	**1**		i-Pr	$InCl_3$	Acetone, −78	81	**7d**	82:18	
9	**2**		Ph	CH_3SnCl_3	CH_2Cl_2, 25	80	**8a**	94:6	
10	**2**		Ph	CH_3SnCl_3	CH_2Cl_2, −78	79	**8a**	96:4	
11	**2**		C_6H_{11}	CH_3SnCl_3	CH_2Cl_2, 25	82	**8b**	60:40	
12	**2**		C_6H_{11}	CH_3SnCl_3	CH_2Cl_2, −78	76	**8b**	64:36	
13	**2**		Bn	CH_3SnCl_3	CH_2Cl_2, 25	81	**8c**	60:40	
14	**2**		i-Pr	CH_3SnCl_3	CH_2Cl_2, 25	60	**8c**	59:41	
15	**2**		Ph	$InCl_3$	Acetone, −78	79	**8a**	86:14	
16	**2**		C_6H_{11}	$InCl_3$	Acetone, −78	79	**8b**	92:8	
17	**2**		Bn	$InCl_3$	Acetone, −78	84	**8c**	88:12	
18	**2**		i-Pr	$InCl_3$	Acetone, −78	73	**8d**	94:6	
19	**3**	72:28	Ph	CH_3SnCl_3	CH_2Cl_2, 25	85	**9a**	93:7	24:76
20	**3**	46:54	Ph	CH_3SnCl_3	CH_2Cl_2, 25	83	**9a**	94:6	59:41
21	**3**	69:31	C_6H_{11}	CH_3SnCl_3	CH_2Cl_2, 25	78	**9b**	94:6	30:70
22	**3**	44:56	C_6H_{11}	CH_3SnCl_3	CH_2Cl_2, 25	75	**9b**	93:7	54:46
23	**3**	69:31	Bn	CH_3SnCl_3	CH_2Cl_2, 25	79	**9c**	73:27	35:65
24	**3**	35:65	Bn	CH_3SnCl_3	CH_2Cl_2, 25	81	**9c**	61:39	60:40
25	**3**	69:31	i-Pr	CH_3SnCl_3	CH_2Cl_2, 25	70	**9d**	93:7	31:69
26	**3**	44:56	i-Pr	CH_3SnCl_3	CH_2Cl_2, 25	65	**9d**	94:6	54:46
27	**3**	69:31	Ph	$InCl_3$	Acetone, −78	78	**9a**	89:11	47:53
28	**3**	40:60	Ph	$InCl_3$	Acetone, −78	73	**9a**	96:4	55:45
29	**3**	69:31	C_6H_{11}	$InCl_3$	Acetone, −78	76	**9b**	92:8	43:57
30	**3**	40:60	C_6H_{11}	$InCl_3$	Acetone, −78	71	**9b**	92:8	58:42
31	**3**	69:31	Bn	$InCl_3$	Acetone, −78	71	**9c**	82:18	42:58
32	**3**	35:65	Bn	$InCl_3$	Acetone, −78	74	**9c**	81:19	54:46
33	**3**	69:31	i-Pr	$InCl_3$	Acetone, −78	74	**9d**	92:8	46:54
34	**3**	40:60	i-Pr	$InCl_3$	Acetone, −78	69	**9d**	96:4	60:40

the *E* isomer reacted marginally faster than the *Z*, presumably due to the enhanced σ–π conjugation available to the *quasi*-axial carbon–tin bond in this isomer.[5] Interestingly, the product of this partial reaction did not isomerise on standing (7 days, *ca*. 25 °C) suggesting that isomerisation requires at least a trace of free Lewis acid and is a bimolecular process.

Aldehyde addition to the transmetallation products **4**–**6** was examined (Scheme 3, Table 2) and compared to results obtained with indium(III) chloride in acetone. Cyclic allylic stannanes **1**–**3**



1; *n* = 0, R^1 = H
2; *n* = 1, R^1 = H
3; *n* = 1, R^1 = Me
a; R^2 = Ph
b; R^2 = C_6H_{11}
c; R^2 = Bn
d; R^2 = i-Pr

7; *n* = 0, R^1 = H
8; *n* = 1, R^1 = H
9; *n* = 1, R^1 = Me

Scheme 3

were first treated with the Lewis acid followed by the aldehyde under varying conditions (Table 2). Hydrolysis with water provided the corresponding homoallylic alcohols **7**–**9** in good yields. The relative stereochemistry of these compounds was assigned based on ^1H and ^{13}C NMR spectral comparisons which have been previously described.[6] These reactions provided predominantly *erythro* products in all cases, with highest diastereoselectivity observed for methyltin trichloride, benzaldehyde and all three stannanes (de = 86–88%) and with indium(III) chloride and the cyclohex-2-enylstannanes **2** and **3** (de = 72–92%). The lowest diastereoselectivity was observed for methyltin trichloride mediated reactions of aliphatic aldehydes to stannane **1** (de = 10–18%). Temperature had little effect on the methyltin trichloride promoted reactions (entries 9, 10 and 11, 12).

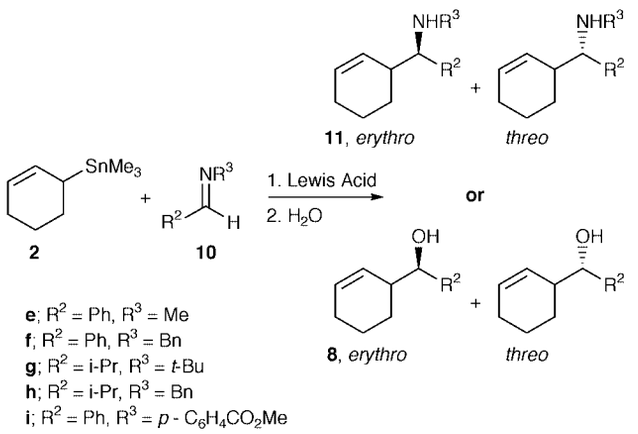
The stereochemistry of aldehyde addition was again examined with isomeric mixtures of stannane **3** (entries 19–34). These reactions indicated overall stereochemical inversion in all cases, although with some stereoleakage (both *E* to *Z* and *Z* to *E*) for the $InCl_3$ promoted reactions.

The Lewis acid promoted addition of imines to acyclic allylic stannanes has been reported.[7] We observed the $BF_3{\cdot}OEt_2$ mediated addition of imines **10** to cyclic allylic stannane **2** (Scheme 4) to provide amine **11** in good yield and with *erythro* diastereoselectivity (Table 3, entries 6 and 7). This reaction

Table 3 Reaction between cyclohex-2-enyltrimethylstannane **2** and imines **10**

Entry	Imine	Lewis acid	*T*/°C	Product	Yield (%)	*erythro* : *threo*
1	**10e**	CH_3SnCl_3	25	**8a**	78	96 : 4
2[a]	**10e**	CH_3SnCl_3	−78	**8a**	72	96 : 4
3	**10f**	CH_3SnCl_3	25	**8a**	77	95 : 5
4	**10g**	CH_3SnCl_3	25	**8d**	79	42 : 58
5	**10h**	CH_3SnCl_3	25	**8d**	73	41 : 59
6	**10f**	$BF_3{\cdot}OEt_2$	−78	**11f**	42	78 : 22
7	**10i**	$BF_3{\cdot}OEt_2$	−78	**11i**	81	60 : 40

[a] Reverse order of reagent addition.



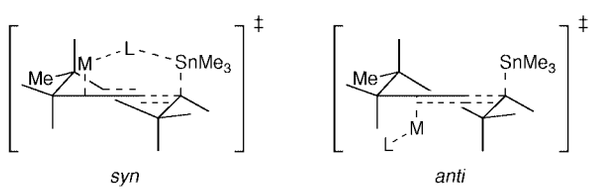
Scheme 4

most probably proceeds *via* an acyclic transition state involving antiperiplanar addition of the Lewis acid–imine complex to the allylic stannane.[8] Surprisingly, the corresponding methyltin trichloride promoted reaction did not provide amines **11**, but homoallylic alcohols **8** in good yield and with the same levels of *erythro* diastereoselectivity observed with the corresponding aldehydes. Either adding the imine to the preformed transmetallation adduct **5** (entries 1, 3–5, Table 3) or adding stannane **2** to the imine–methyltin trichloride complex at −78 °C (entry 2), made no difference to the outcome. An NMR study conducted in CD_2Cl_2 revealed that no reaction occurred until addition of water, whereupon there was a rapid hydrolysis of the imine and reaction of the newly formed aldehyde with the transmetallation product, **5**.

Discussion

Transmetallation

We[3] and others[9] have speculated that a transmetallation reaction between an allylic stannane and a Lewis acid would occur *via* a *syn*, metallo–ene transition state involving tin–halogen coordination (Scheme 5). The reaction of (*E*)- and (*Z*)-**3** with

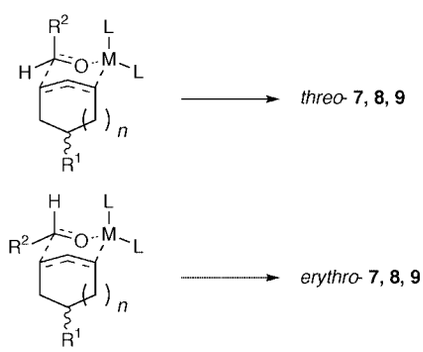


Scheme 5

methyltin trichloride, however, indicates *anti* approach of the electrophile as observed with other electrophiles (such as H^+) and as predicted for a dominating LUMO–HOMO interaction in a concerted S_E2' process.[5] Although the analogous indium(III) chloride transmetallation intermediate could not be observed by NMR, *anti* attack can be inferred from the stereochemical outcome of subsequent aldehyde addition. This interpretation is also consistent with literature results, albeit for substrates bearing coordinating functionality.[1c]

Aldehyde addition

We have previously reported *syn–erythro* diastereoselectivity for the high-pressure (9 kbar) addition of benzaldehyde to stannane **3**.[10] This result was interpreted in terms of a metallo–ene aldehyde addition involving tin–oxygen coordination. It seems probable that the addition of aldehydes to transmetallation products occurs *via* the same, cyclic transition states (Scheme 6). The formation of predominantly *erythro* isomers is



Scheme 6

consistent with an unfavourable pseudo 1,3-diaxial interaction between the alkyl or aryl group of the aldehyde and either chloride or methyl on the metal in the transition state leading to the *threo* product. While imines are insufficiently reactive to add to the transmetallation adducts, they do provide a stable, alternative substrate to aldehydes which may be useful in particular situations. Interestingly, the respectable yields of homoallylic alcohols **8** (≥72%) obtained from imine addition indicate that water hydrolysis of the imine followed by addition to the transmetallation adduct is faster than reaction of the latter with water.

In conclusion, the stereochemistry of Lewis acid promoted addition of aldehydes to allylic stannanes has been investigated for substrates not bearing coordinating functionality. Initial transmetallation proceeds *via* a predominantly *anti* electrophilic substitution, which is most probably stereoelectronically directed. This step is followed by metallo–ene, *syn* aldehyde addition that proceeds with a sterically derived *erythro* selectivity.

Experimental

General instructions and the preparation of allylic stannanes (**1**–**3**) have been given.[11]

NMR study of transmetallation

A precooled (−78 °C) solution of methyltrichlorostannane (1.0 mmol) in CD_2Cl_2 (1.0 mL) was added to a precooled (−78 °C)

Table 4 ^{13}C NMR data (δ/ppm) for transmetallation products[a]

Compound	C1	C2	C3	C4	C5	C6	C other
4[b]	49.2	129.1	133.3	32.6	27.1		−0.4
5[b]	48.8	125.0	129.8	25.6	23.1	15.1	−0.5
(*Z*)-**6**[c]	41.1 (510.5)	129.9 (96.2)	123.5 (66.6)	33.0	29.1 (80.0)	33.1	21.5 (118.4), 4.27
(*E*)-**6**[c]	43.8 (469.8)	128.7 (103.6)	124.1 (70.3)	33.27	28.9 (21.0)	33.7	21.8 (125.8), 5.02

[a] Values in parentheses are ^{119}Sn–^{13}C coupling constants. [b] Acquired in CD_2Cl_2 as solvent. [c] Acquired in $CDCl_3$ as solvent.

solution of stannane **1**–**3** (1.0 mmol) in CD_2Cl_2 (1.0 mL) in a 5 mm NMR tube. This tube was inverted several times to allow mixing and transferred to the NMR probe which was also precooled to −78 °C. Spectra were acquired immediately (Table 4).

Methyltrichlorostannane promoted addition of aldehydes; typical procedure

1-(Cyclopent-2-enyl)-1-phenylmethanol 7a. Stannane **1** (1.09 g, 4.71 mmol) in anhydrous dichloromethane (5.0 mL) was added dropwise to a stirred solution of methyltrichlorostannane (1.13 g, 4.71 mmol) in dichloromethane (20 mL) at 25 °C under a nitrogen atmosphere. A solution of benzaldehyde (0.5 g, 4.71 mmol) in dichloromethane (5.0 mL) was added dropwise after 30 min. The reaction was left to stir for 1 h and then quenched with water and extracted with dichloromethane (4 × 25 mL). The organic layers were dried (Na_2SO_4), condensed and the residue purified by Kugelrohr distillation (oven temp. 130 °C/0.5 Torr) to give a clear oil (0.698 g, 85.0%) (Found: C, 82.5; H, 8.1. $C_{12}H_{14}O$ requires C, 82.7; H, 8.1%); δ_H (200 MHz; $CDCl_3$) 1.80–2.05 (2H, m, CH_2), 2.14 (1H, br s, OH), 2.28–2.50 (2H, m, CH_2), 3.04–3.12 (1H, m, CH), 4.32 (1H, d, *J* 6.35, C*H*OH *threo*), 4.56 (1H, d, *J* 6.6, C*H*OH *erythro*), 5.38–5.43 (1H, m, CH *erythro*), 5.75–5.80 (1H, m, CH *threo*), 5.83–5.88 (1H, m, CH *erythro*), 5.97–6.00 (1H, m, CH *threo*), 7.22–7.44 (5H, m, Ph); δ_C (50 MHz; $CDCl_3$) *erythro*: 25.19, 32.28, 53.99, 77.12, 131.38, 133.66, 126.38, 127.39, 127.39, 128.28, 128.28, 143.60; *threo*: 26.48, 31.05, 53.51, 130.64, 133.84, 126.27, 127.01, 127.01, 128.28, 143.60.

Indium(III) chloride promoted addition of aldehydes; typical procedure

1-Cyclohexyl-1-(cyclopent-2-enyl)methanol 7b. Cyclohexanecarbaldehyde (0.5 g, 4.46 mmol) in acetone (5 mL) was added to a suspension of indium(III) chloride (0.986 g, 4.46 mmol) in acetone (20 mL) and stirred at 25 °C under a nitrogen atmosphere for 5 min. This solution was then cooled to −78 °C and stannane **1** (1.03 g, 4.46 mmol) in acetone (5 mL) added dropwise. The mixture was warmed to 25 °C over 6 h, quenched with water (10 mL) followed by aq. KF (10%, 10 mL), filtered and extracted with dichloromethane (3 × 25 mL). The organic layers were dried (Na_2SO_4), condensed and the residue purified by Kugelrohr distillation (oven temp. 105 °C/0.25 Torr) to give a clear oil (0.683 g, 85.0%) (Found: C, 79.5; H, 11.2. $C_{12}H_{20}O$ requires C, 79.9; H, 11.2%); δ_H (200 MHz; $CDCl_3$) 0.92–1.48 (6H, m), 1.52–1.77 (6H, m), 1.81–2.00 (2H, m, CH_2), 2.17–2.97 (2H, m, CH_2), 3.13 (1H, dd, *J* 5.94, 7.16, C*H*OH *erythro*), 3.29 (1H, dd, *J* 4.07, 6.43, C*H*OH *threo*), 5.52–5.57 (1H, m, CH *threo*), 5.69–5.73 (1H, m, CH *erythro*), 5.83–5.90 (1H, m, CH *erythro* and *threo*); δ_C (50 MHz; $CDCl_3$) *erythro*: 25.54, 32.43, 48.40, 79.61, 130.20, 133.88, 26.11, 26.54, 26.98, 28.03, 30.04, 42.29; *threo*: 26.54, 29.60, 48.87, 77.76, 131.95, 133.62, 23.34, 26.11, 26.54, 26.36, 28.58, 41.36.

1-(Cyclopent-2-enyl)-2-phenylethanol 7c. Kugelrohr distillation (oven temp. 130 °C/0.5 Torr) (Found: C, 82.8; H, 8.5. $C_{13}H_{16}O$ requires C, 82.9; H, 8.6%); δ_H (200 MHz; $CDCl_3$) 1.65–2.10 (4H, m, CH_2CH_2), 2.35–2.42 (2H, m, CH, OH), 2.67–2.93 (2H, m, CH_2), 3.79 (1H, m, C*H*OH *threo*), 3.80 (1H, m, C*H*OH *erythro*), 5.65–5.69 (1H, m, CH), 5.85–5.95 (1H, m, CH), 7.22–7.37 (5H, m, Ph); δ_C (50 MHz; $CDCl_3$) *erythro*: 24.03, 32.47, 51.37, 74.91, 126.41, 131.44, 128.57, 42.30, 129.47, 130.47, 138.91; *threo*: 26.50, 30.91, 51.37, 76.28, 128.13, 133.71, 41.59, 128.57, 129.47, 129.71, 138.91.

1-(Cyclopent-2-enyl)-2-methylpropan-1-ol 7d. Kugelrohr distillation (oven temp. 105 °C/10 Torr) (Found: C, 76.9; H, 10.9. $C_9H_{16}O$ requires C, 77.1; H, 11.5%); δ_H (200 MHz; $CDCl_3$) 0.93 (6H, d, *J* 5.38, CH_3), 1.52–1.80 (2H, m, CH_2), 1.81–2.00 (1H, m, CH), 2.10–2.52 (2H, CH_2), 2.86–2.93 (1H, m, CH), 3.09 (1H, dd, *J* 6.11, 6.03, C*H*OH *erythro*), 3.23 (1H, dd, *J* 6.02, 3.91, C*H*OH *threo*), 5.51–5.56 (1H, m, CH *threo*), 5.57–5.74 (1H, m, CH), 5.77–5.87 (1H, m, CH *erythro* and *threo*); δ_C (50 MHz; $CDCl_3$) *erythro*: 26.97, 32.33, 49.01, 80.36, 130.34, 133.71, 17.33, 19.82, 32.17; *threo*: 23.67, 31.49, 49.43, 78.72, 131.84, 133.51, 17.80, 19.56, 30.71.

1-(Cyclohex-2′-enyl)-1-phenylmethanol 8a. Kugelrohr distillation (oven temp. 110 °C/0.2 Torr, lit.,[6] 165 °C/0.3 Torr). δ_H (200 MHz; $CDCl_3$) *erythro*: 1.50–1.78 (4H, m, CH_2), 2.01–2.11 (3H, m, CH_2, OH), 2.51 (1H, m, CH), 4.57 (1H, d, *J* 6.59, C*H*OH), 5.36–5.42 (1H, dd, *J* 10.2 2.0, CH), 5.73–5.87 (1H, dq, *J* 10.1 3.0, CH), 7.27–7.34 (5H, m, C_6H_5); *threo*: δ_H 1.50–1.78 (4H, m, CH_2), 2.01–2.11 (3H, m, CH_2, OH), 2.65 (1H, m, CH), 4.48 (1H, d, *J* 7.0, C*H*OH), 5.23–5.35 (1H, dd, *J* 10.1 2.0, CH), 5.57–5.66 (1H, dq, *J* 8.63 3.0, CH), 7.27–7.34 (5H, m, C_6H_5); δ_C (50 MHz; $CDCl_3$) *erythro*: 20.83, 22.32, 26.01, 40.19, 77.35, 126.52, 130.72, 127.21, 127.36, 127.80, 128.12, 129.87, 143.01; *threo*: 21.19, 23.99, 25.31, 43.06, 77.56, 126.69, 130.36, 127.21, 127.36, 127.80, 128.12, 129.95, 143.01.

1-(Cyclohex-2′-enyl)-1-cyclohexylmethanol 8b. Kugelrohr distillation (oven temp. 120 °C/1 Torr) (Found: C, 80.35; H, 11.4. $C_{13}H_{22}O$ requires C, 80.35; H, 11.4%); δ_H (200 MHz; $CDCl_3$) *erythro*: 0.97–1.97 (18H, m, CH_2, CH, OH), 2.32 (1H, m, CH), 3.11 (1H, t, *J* 5.61, C*H*OH), 5.70–5.75 (1H, dd, *J* 10.83 3.0, CH), 5.83–5.92 (1H, m, CH); *threo*: 0.97–1.97 (18H, m, CH_2, CH, OH), 2.32 (1H, m, CH), 3.25 (1H, dd, *J* 4.38, 4.47, C*H*OH), 5.46–5.51 (1H, dd, *J* 10.17 2.0, CH), 5.57–5.62 (1H, dd, *J* 10.1 2.0, CH); δ_C (50 MHz; $CDCl_3$) *erythro*: 21.97, 25.23, 26.76, 40.73, 79.60, 126.92, 130.34, 26.18, 26.43, 26.53, 27.78, 30.00, 37.82; *threo*: 21.39, 25.42, 26.32, 39.79, 78.64, 129.32, 130.89, 26.18, 26.31, 26.77, 28.79, 29.42, 37.96.

1-(Cyclohex-2′-enyl)-2-phenylethanol 8c. Kugelrohr distillation (oven temp. 149 °C/0.5 Torr) (Found: C, 83.1; H, 9.05. $C_{14}H_{18}O$ requires C, 83.1; 9.0%); δ_H (200 MHz; $CDCl_3$) 1.47–1.65 (2H, m, CH_2), 1.70–1.87 (3H, m, CH-CH_2), 2.05 (2H, m, CH_2), 2.64–2.78 (1H, m, PhC*H*), 2.85–2.96 (1H, m, PhC*H*), 3.65–3.74 (1H, m, C*H*OH *erythro*), 3.77–3.83 (1H, m, C*H*OH *threo*), 5.63–5.68 (1H, m, CH), 5.80–5.96 (1H, m, CH), 7.20–7.44 (5H, m, C_6H_5); δ_C (50 MHz; $CDCl_3$) *erythro*: 21.88, 23.30, 25.37, 40.78, 76.30, 127.07, 129.88, 41.18, 126.41, 128.60, 129.46, 139.14; *threo*: 21.45, 25.92, 26.02, 40.45, 40.78, 75.53, 126.42, 130.29, 41.18, 126.41, 128.60, 129.46, 139.14.

1-(Cyclohex-2′-enyl)-2-methylpropan-1-ol 8d. Kugelrohr distillation (oven temp. 100 °C/5 Torr, lit.,[6] 100 °C/5 Torr) δ_H (200 MHz; $CDCl_3$) *erythro*: 0.91 (6H, d, *J* 6.68, CH_3), 1.39–1.97

(8H, m, CH_2, CH, OH), 2.28 (1H, m, CH), 3.05 (1H, t, *J* 5.82, C*H*OH), 5.70–5.86 (2H, m, CH=CH); *threo*: 0.91 (6H, d, *J* 6.7, CH_3), 1.392–1.97 (8H, m, CH_2, CH, OH), 2.28 (1H, m, CH), 3.18 (1H, m, C*H*OH), 5.44–5.70 (2H, m, CH=CH); δ_C (50 MHz; $CDCl_3$) *erythro*: 21.88, 25.28, 26.69, 38.47, 80.26, 127.10, 130.02, 17.00, 19.81, 30.66; *threo*: 21.26, 22.21, 24.58, 38.47, 79.50, 129.43, 130.42, 18.20, 19.45, 30.03.

1-(5′-Methylcyclohex-2′-enyl)-1-phenylmethanol 9a. Kugelrohr distillation (oven temp. 130 °C/0.06 Torr) (Found: C, 82.9; H, 8.9. $C_{14}H_{18}O$ requires C, 83.1; H, 9.0%); δ_H (200 MHz; $CDCl_3$) coincident 7.25–7.39 (5H, m, aromatic protons), 1.8–2.2 (2H, m, $C4H_2$), 1.55–1.72 (2H, m, $C6H_2$), 1.34 (1H, m, C5H); *cis erythro*: 5.82 (1H, m, =C*H*), 5.42 (1H, d, *J* 10.2, =C*H*), 4.55 (1H, d, *J* 6.2, C*H*OH), 2.61 (1H, m, CH), 0.95 (3H, d, *J* 5.94, CH_3); *trans erythro*: 5.70 (1H, m, =C*H*), 5.11 (1H, d, *J* 8.6, =C*H*), 4.41 (1H, d, *J* 7.8, C*H*OH), 2.50 (1H, m, CH), 0.968 (3H, d, *J* 6.35, CH_3); *cis threo*: 5.80 (1H, m, =C*H*), 4.36 (1H, d, *J* 7.0, C*H*OH); *trans threo*: 5.7 (1H, m, =C*H*), 3.90 (1H, d, *J* 5.4, C*H*OH); δ_C (50 MHz; $CDCl_3$; 25 °C) *cis erythro*: 22.25, 28.66, 32.70, 34.11, 44.48, 77.57, 127.92, 129.95; *cis threo*: 22.29, 28.79, 34.18, 35.13, 44.25, 77.77, 126.79, 129.27; *trans erythro*: 21.15, 24.68, 31.22, 33.27, 41.49, 76.80, 126.84, 130.05; *trans threo*: 20.67, 24.85, 32.88, 33.04, 40.99, 78.10, 126.24, 130.51.

1-(5′-Methylcyclohex-2′-enyl)-1-cyclohexylmethanol 9b. Kugelrohr distillation (oven temp. 140 °C/0.2 Torr) (Found: C, 80.6; H, 11.6. $C_{14}H_{24}O$ requires C, 80.7; H, 11.6%); δ_H (200 MHz; $CDCl_3$) *cis erythro*: 0.95 (3H, d, *J* 4.48, CH_3), 1.02–2.16 (17H, m, CH_2, CH, OH), 2.37 (1H, m, CH), 3.04 (1H, t, *J* 5.7, C*H*OH), 5.65–5.73 (2H, m, CH=CH); *trans erythro*: 0.92 (3H, d, *J* 6.59, CH_3), 1.02–2.16 (17H, m, CH_2, CH, OH), 2.37 (1H, m, CH), 3.15 (1H, t, *J* 5.7, C*H*OH), 5.76–5.86 (2H, m, CH=CH); δ_C (50 MHz; $CDCl_3$) *cis erythro*: 22.50, 26.18, 34.22, 35.43, 41.31, 79.21, 126.88, 129.58, 26.42, 27.74, 27.74, 29.99, 30.07, 39.25; *trans erythro*: 21.01, 25.38, 33.07, 34.38, 40.55, 80.26, 125.83, 129.80, 26.18, 26.54, 26.54, 29.09, 29.02, 39.25.

1-(5′-Methylcyclohex-2′-enyl)-1-phenylethanol 9c. Kugelrohr distillation (oven temp. 150 °C/0.15 Torr) (Found: C, 83.1; H, 9.35. $C_{15}H_{20}O$ requires C, 83.3; H, 9.3%); δ_H (200 MHz; $CDCl_3$) *cis erythro*: 1.05 (3H, d, *J* 5.86, CH_3), 1.16–1.40 (1H, m, C*H*CH_3), 1.67–1.88 (4H, m, CH_2), 2.01–2.26 (1H, m, CH), 2.41 (1H, br s, OH), 3.83 (1H, m, *J* 4.26, C*H*OH), 5.60–5.79 (1H, m, CH), 5.85–5.93 (1H, m, CH), 7.22–7.35 (5H, m, C_6H_5); *trans erythro*: 1.03 (3H, d, *J* 4.81, CH_3), 1.16–1.40 (1H, m, C*H*CH_3), 1.67–1.88 (4H, m, CH_2), 2.01–2.26 (1H, m, CH), 2.41 (1H, br s, OH), 3.70 (1H, m, C*H*OH), 5.60–5.79 (1H, m, CH), 5.85–5.93 (1H, m, CH), 7.22–7.35 (5H, m, C_6H_5); δ_C (50 MHz; $CDCl_3$) *cis erythro*: 22.61, 28.80, 32.02, 34.19, 42.13, 126.45, 128.52, 40.23, 128.62, 129.39, 129.93, 139.17; *trans erythro*: 22.61, 28.94, 33.13, 34.29, 42.03, 126.45, 128.89, 40.23, 128.62, 129.39, 129.93, 139.17; *cis threo*: 21.05, 25.45, 33.13, 34.29, 41.81, 126.00, 127.42, 38.44, 128.62, 129.39, 129.93, 139.17; *trans threo*: 21.28, 25.08, 33.06, 33.37, 41.03, 126.70, 127.72, 39.32, 128.62, 129.39, 129.93, 139.17.

1-(5′-Methylcyclohex-2′-enyl)-2-methylpropan-1-ol 9d. Yield 74.2%, Kugelrohr distillation (oven temp. 105 °C/5 Torr, lit.[6] oven temp. 120 °C/1 Torr) (Found: C, 80.6; H, 11.6. $C_{14}H_{24}O$ requires C, 80.7; H, 11.6%); δ_H (200 MHz; $CDCl_3$) *cis erythro*: 0.93 (6H, d, *J* 6.67, CH_3), 0.98 (3H, d, *J* 6.67, CH_3), 1.34–2.18 (7H, m, CH_2, CH, OH), 2.33 (1H, m, CH), 3.02 (1H, t, *J* 5.78, C*H*OH), 5.65–5.85 (2H, m, CH=CH); *trans erythro*: 0.92 (6H, d, *J* 6.92, CH_3), 0.95 (3H, d, *J* 6.52, CH_3), 1.34–2.18 (7H, m, CH_2, CH, OH), 2.33 (1H, m, CH), 3.14 (1H, t, *J* 5.7, C*H*OH), 5.65–5.86 (2H, m, CH=CH); δ_C (50 MHz; $CDCl_3$) *cis erythro*: 22.47, 28.97, 30.54, 33.09, 39.91, 80.01, 126.89, 129.50, 17.08, 19.81, 35.42; *trans erythro*: 21.02, 25.28, 31.25, 34.18, 39.91, 80.95, 125.94, 129.69, 17.08, 19.81, 35.96.

Imine synthesis; typical procedure

***N*-*tert*-Butyl(2-methylpropylidene)amine 10g.** 2-Methylpropanal (14.4 g, 0.2 mol) was added dropwise to *tert*-butylamine (14.6 g, 0.2 mol) over 30 min. The temperature rose from 25 to 40 °C and an aqueous layer separated towards the end of the addition. The organic layer was separated and stirred with Na_2SO_4 (anhydrous) for 5 h. The mixture was then filtered and the filtrate distilled to give the imine as a colourless liquid (16.51 g, 65%) bp 56 °C/75 Torr (lit.,[12] 56 °C/75 Torr); δ_H (200 MHz; $CDCl_3$) 7.30–7.33 (1H, d, *J* 6.02, N=CH), 2.30 (1H, m, CH), 0.85–1.16 (16H, m); δ_C (50 MHz; $CDCl_3$) 19.63, 29.62, 34.46, 55.99, 163.68.

***N*-Benzyl(2-methylpropylidene)amine 10h.** Yield 65.12%, bp 84 °C/2 Torr (lit.,[13] 105 °C/4 Torr); δ_H (200 MHz; $CDCl_3$) 7.66–7.68 (1H, d, *J* 5.13, N=CH), 7.24–7.33 (5H, m, Ph), 4.57 (2H, s, CH_2), 2.50–2.53 (1H, m, CH), 1.10–1.14 (6H, d, *J* 8.71, $C(CH_3)_2$); δ_C (50 MHz; $CDCl_3$) 19.37, 34.16, 64.83, 126.85, 127.10, 127.70, 127.80, 128.45, 139.51, 170.99.

Methyl *N*-benzylideneaminobenzoate 10i. Yield 85%, mp 103–104 °C (lit.,[14] 107–108 °C); δ_H (200 MHz; $CDCl_3$) 3.93 (3H, s, CH_3), 7.22 (2H, AA′XX′, Ar), 7.49 (3H, m, Ar), 7.92 (2H, m, Ar), 8.09 (2H, AA′XX′, Ar), 8.44 (1H, s, N=CH); δ_C (50 MHz; $CDCl_3$) 52.03, 113.82, 120.73, 128.92, 129.11, 129.77, 130.92, 131.63, 131.95, 134.50, 161.75, 192.44.

Boron trifluoride–diethyl ether promoted addition of imines; typical procedure

***N*-Benzyl-1-(cyclohex-2-enyl)-1-phenylmethanamine 11f.** *N*-Benzylbenzylideneamine (0.5 g, 2.56 mmol) in dichloromethane (5 mL) was cooled to −78 °C and boron trifluoride etherate (0.365 g, 2.56 mmol) was added dropwise. The mixture was stirred for 2.5 h and cyclohex-2-enyltrimethylstanne **2** (0.627 g, 2.56 mmol) in dichloromethane (5 mL) was added. The reaction was stirred for 1 h at −78 °C and then at 25 °C for 16 h. It was then quenched with saturated $NaHCO_3$ (aq) and extracted with dichloromethane (4 × 25 mL). The organic layers were dried (Na_2SO_4), condensed and the residue purified by Kugelrohr distillation (oven temp. 160 °C/0.2 Torr) to give a clear oil (0.30 g, 42.3%) (Found: C, 86.5; H, 8.5; N, 4.8. $C_{20}H_{23}N$ requires C, 86.6; H, 8.4; N, 5.05%); δ_H (200 MHz; $CDCl_3$) 1.20–1.99 (7H, m, CH_2, NH), 2.39 (1H, m, CH), 3.46–3.77 (3H, CH_2, CH), 5.73–5.84 (1H, m, CH), 5.95–6.01 (1H, dd, *J* 9.72, 2.0, CH), 7.21–7.42 (10H, m, 2Ph); δ_C (50 MHz; $CDCl_3$) *erythro*: 21.63, 25.45, 26.83, 42.14, 51.69, 67.05, 126.81, 129.51, 126.92, 127.72, 127.82, 128.18, 128.19, 128.27, 128.73, 128.81, 140.93, 143.08; *threo*: 21.77, 24.68, 26.83, 42.59, 51.69, 66.39, 126.81, 129.51, 126.92, 127.72, 127.82, 128.18, 128.19, 128.27, 128.73, 128.81, 140.93, 143.08.

***N*-(Methoxycarbonylphenyl)-1-(cyclohex-2-enyl)-1-phenylmethanamine 11i.** Yield 80.5%, mp 119–120 °C (Found: C, 78.2; H, 7.3; N, 4.2. $C_{21}H_{23}O_2N$ requires C, 78.5; H, 7.2; N, 4.4%); δ_H (200 MHz; $CDCl_3$) 1.54 (2H, m, CH_2), 1.81 (2H, m, CH_2), 2.04 (2H, m, CH_2), 2.64 (1H, m, CH), 3.81 (3H, s, OCH_3), 4.40 (1H, s, NH), 4.45 (1H, m, CH), 5.84–5.97 (1H, CH), 6.45 (2H, d, *J* 8.71, C_6H_5), 7.30 (5H, m, C_6H_5), 7.76 (2H, AA′XX′, C_6H_4); δ_C (50 MHz; $CDCl_3$) *erythro*: 21.84, 25.23, 27.78, 42.95, 51.51, 60.94, 127.12, 131.98, 112.12, 118.48, 126.67, 128.54, 131.44, 141.63, 151.36, 167.32; *threo*: 21.70, 24.06, 25.23, 42.54, 51.51, 61.52, 125.43, 130.60, 112.50, 118.20, 126.88, 128.70, 131.32, 141.14, 151.58, 167.32.

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