DOI: 10.1002/ejoc.201300231

Enantioselective Synthesis of Both Enantiomers of Chiral Allenes Using Chiral *N*-Methylcamphanyl Piperazine Templates

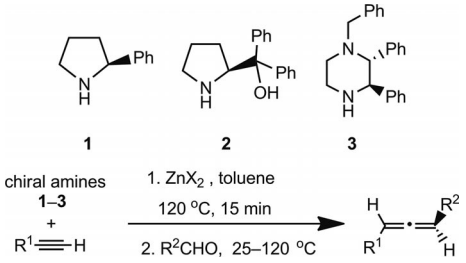
Mariappan Periasamy,*[a] Polimera Obula Reddy,[a] and Nalluri Sanjeevakumar[a]

Keywords: Allenes / Alkynes / Chirality / Zinc / Enantioselectivity

The reaction of unsubstitued camphanyl-piperazine **4** with $ZnCl_2$, phenylacetylene, and benzaldehyde in toluene gave the corresponding dipropargylamine (i.e., **15**) with opposite configurations at the newly formed stereogenic centres, which, upon reaction with ZnI_2 resulted in the formation of a racemic mixture of 1,3-diphenyl allene in 45 % yield. *N*-Methylcamphanyl-piperazine regioisomer **5**, prepared by selective *N*-methylation of the NH moiety attached to the stereogenic centre with (*S*)-configuration, upon reaction with $ZnCl_2$, phenylacetylene, and benzaldehyde in toluene, gave the corresponding propargylamine in 90 % yield, with an (*S*)-configuration at the newly formed stereogenic centre, and upon subsequent reaction with ZnI_2, this intermediate gave (*R*)-1,3-diphenyl allene in 52 % yield and with 96 % *ee*. Reaction of *N*-methylcamphanyl-piperazine isomer **5** with several 1-alkynes and aldehydes in the presence of $ZnBr_2$ gave the corresponding (*R*)-allenes in 40–75 % yield and 79–99 % *ee*. In contrast, regioisomeric *N*-methylcamphanyl-piperazine **6** reacted with $ZnBr_2$ to give the corresponding (*S*)-allenes in 38–71 % yield and with 79–99 % *ee*. The opposite chiral discriminating abilities of the two NH moieties in camphanyl-piperazines was confirmed by single-crystal X-ray analysis of the propargylamines formed. The results are discussed considering mechanisms involving the in situ formation of alkynylzinc halides, followed by diastereoselective addition to chiral iminium ion derivatives to give the corresponding propargylamines, and subsequent conversion to chiral allenes by an intramolecular 1,5-hydrogen shift.

Introduction

Allenes are versatile functional groups that could act as useful synthons for synthetic manipulations, with the potential for conversion to chiral molecules with asymmetric centers.[1] Chiral allene structural motifs are also present in several biologically active natural products and pharmaceuticals.[2] For decades, chiral allenes have been prepared by the general reaction of propargyl alcohol derivatives with nucleophiles by S_N2 addition. Generally, the methods available to access enantiomerically enriched allenes require multi-step synthetic operations.[3] Metal-catalysed enantioselective synthesis of chiral allenes from chiral propargylamines using gold[4a] and silver(I)[4b] complexes and zinc halides[4c] by a two-step synthetic protocol have been reported. Although the preparation of a monosubstituted allene from CuBr, a 1-alkyne, and formaldehyde was reported by Crabbe in 1979, the synthesis of racemic 1,3-disubstituted allenes from terminal alkynes, aldehydes, morpholine, and ZnX_2 was reported only very recently.[5] We have recently reported that zinc halides promote the one-pot enantioselective synthesis of chiral allenes using aldehydes, terminal alkynes, and the chiral amine derivatives (**1**–**3**; Scheme 1).[6]



Scheme 1. Synthesis of chiral allenes.

In this paper, we wish to report details of our investigations into the zinc-halide-mediated enantioselective synthesis of both enantiomers of chiral 1,3-disubstituted allenes with up to 99 % *ee* using terminal alkynes, aldehydes, and readily accessible chiral camphanyl-piperazine derivatives (**4**–**6**; Figure 1).

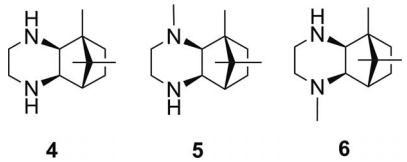


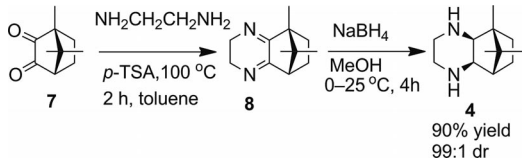
Figure 1. Chiral camphanyl-piperazine derivatives **4**–**6**.

[a] School of Chemistry, University of Hyderabad, Gachibowli, Hyderabad 500046, India
Fax: +91-40-23012460
E-mail: mpsc@uohyd.ernet.in

Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/ejoc.201300231.

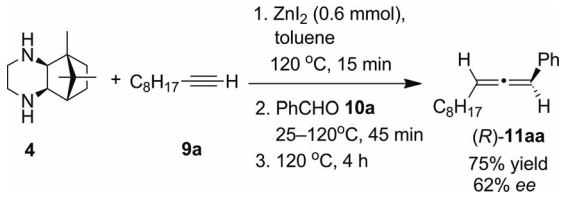
Results and Discussion

Chiral piperazine derivative **4** containing a camphanyl moiety was readily prepared by a recently reported method (Scheme 2).[7]



Scheme 2. Synthesis of chiral piperazine.

We examined the use of chiral cyclic secondary piperazine **4** for the preparation of chiral allenes using various aldehydes, 1-alkynes, and zinc halides. We observed that the reaction of chiral piperazine **4**, 1-decyne (**9a**), and benzaldehyde (**10a**) using ZnI_2 at 120 °C gave (*R*)-allene **11aa** in 75% yield and with 62% *ee* (Scheme 3).



Scheme 3. Reaction of 1-decyne (**9a**) and benzaldehyde (**10a**) with chiral piperazine **4**, promoted by zinc iodide.

We performed several experiments to understand the probable reason for the relatively low enantioselectivity observed using chiral piperazine **4**, compared to the previously reported method using chiral piperazine derivative **3** (Figure 1). The different chiral discrimination abilities of the two secondary amine moieties present in chiral camphanyl-piperazine **4** could lead to the formation of a mixture of chiral propargylamine intermediates **12**, **13**, and **14** (Figure 2), leading to the formation (*R*)-allene **11aa** with only in 62% *ee*.

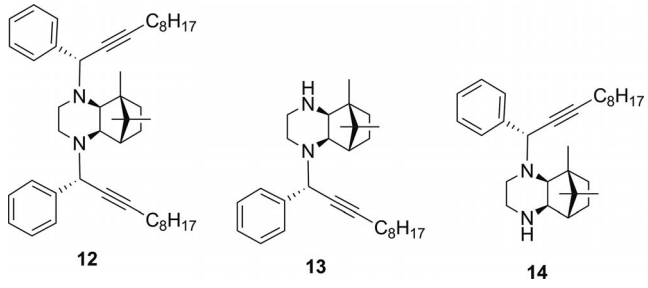
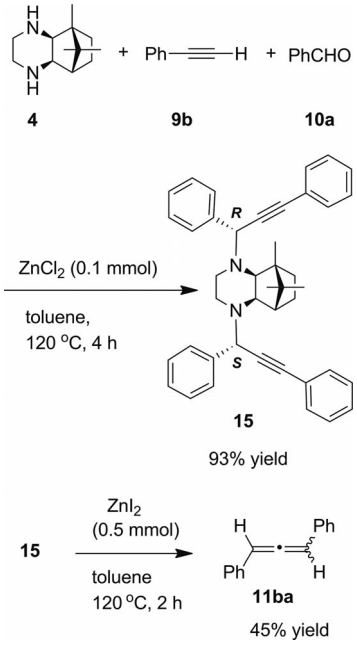


Figure 2. Possible propargylamine intermediates in the reaction of 1-decyne (**9a**) and benzaldehyde (**10a**) with chiral piperazine **4**, promoted by zinc iodide.

To examine this theory, we carried out the reaction of phenylacetylene (**9b**), benzaldehyde (**10a**) and piperazine **4** using $ZnCl_2$ (0.1 mmol) at 120 °C, to stop the reaction at the propargylamine stage (Scheme 4). In this experiment, dipropargylamine intermediate **15** was obtained in 93% yield. The relative configurations at the newly formed stereogenic centres were assigned as (*R,S*) in dipropargylamine **15** by X-ray crystal structure analysis (Figure 3).[10] Interestingly, dipropargylamine **15** reacted with ZnI_2 (0.5 mmol) to give only racemic allene **11ba** in 45% yield.



Scheme 4. Synthesis of dipropargylamine intermediate **15** using phenylacetylene (**9b**), benzaldehyde (**10a**), and piperazine **4** using $ZnCl_2$.

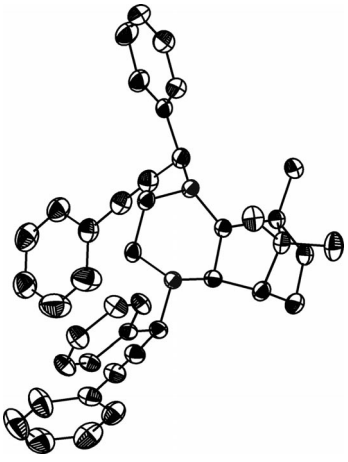
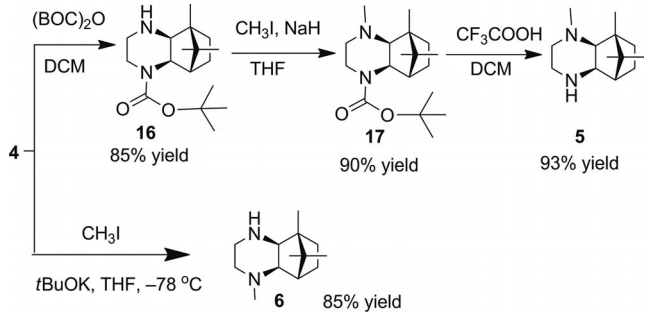


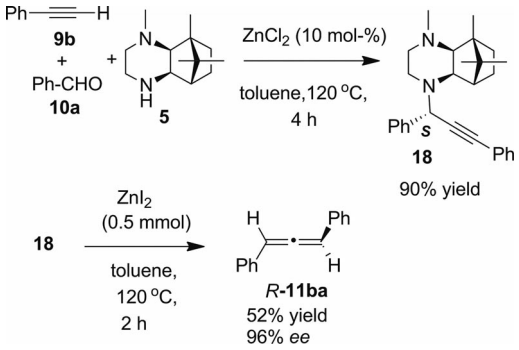
Figure 3. ORTEP representation of dipropargylamine **15** (hydrogen atoms are removed for clarity, and thermal ellipsoids are drawn with 30% probability).

It occurred to us that blocking of one of the secondary amine moieties in chiral piperazine **4** would give better optical purities in this allene transformation. To examine this theory, we developed methods for the synthesis of *N*-methyl-substituted camphanyl-piperazine derivatives **5** and **6** from chiral camphanyl-piperazine **4**. Boc-protection followed by methylation and Boc deprotection gave *N*-methyl piperazine **5** in 93% yield. Direct methylation using *t*BuOK followed by reaction with methyl iodide at –78 °C gave *N*-methyl camphanyl-piperazine **6** in 85% yield (Scheme 5).



Scheme 5. Synthesis of mono-protected piperazine derivatives **5** and **6**.

We observed that the reaction of phenylacetylene (**9b**), benzaldehyde (**10a**), *N*-methylcamphanyl-piperazine **5**, and $ZnCl_2$ (10 mol-%) at 120 °C for 4 h gave propargylamine intermediate **18** in 90% yield and with 99:1 *dr* (Scheme 6). Indeed, as shown in the structure of dipropargylamine **15**, the configuration of the newly formed stereogenic centre in chiral propargylamine **18** has an (*S*)-configuration, as revealed by X-ray single crystal structure analysis (Figure 4).[10] Furthermore, upon reaction with ZnI_2 (0.5 mmol), chiral propargylamine **18** gave (*R*)-allene **11ba** in 52% yield with 96% *ee*.



Scheme 6. Reaction of 1-decyne (**9a**) and benzaldehyde (**10a**) with piperazine **5**, promoted by zinc chloride.

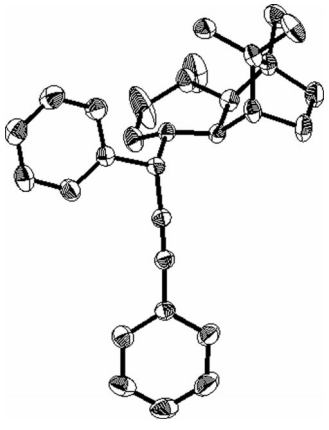
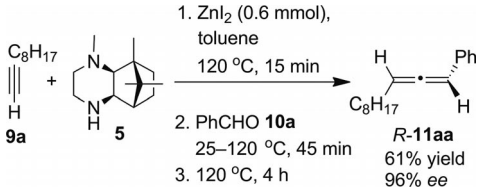


Figure 4. ORTEP representation of propargylamine **18** (hydrogen atoms are removed for clarity, and thermal elipsoids are drawn with 30% probability).

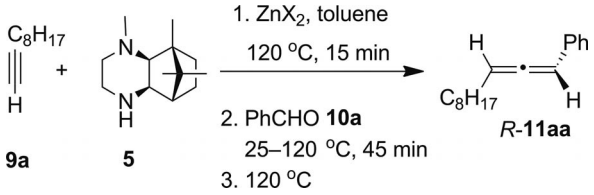
We also observed that the reaction of 1-decyne (**9a**), benzaldehyde (**10a**), and chiral piperazine **5** using ZnI_2 (0.6 mmol) for 4 h at 120 °C led to the formation of (*R*)-allene **11aa** in 61% yield with 96% *ee* (Scheme 7).



Scheme 7. Reaction of 1-decyne (**9a**) and benzaldehyde (**10a**) with piperazine **5**, promoted by zinc iodide.

We carried out this chiral allene transformation under various reaction conditions using different zinc halides with 1-decyne (**9a**), benzaldehyde (**10a**), and piperazine **5**. It is evident that $ZnBr_2$ (0.6 mmol; Table 1, entry 5) gave the best results. Under these optimized conditions, we then performed the reaction using various aldehydes and 1-alkynes (Table 2). A broad range of aldehydes and 1-alkynes were converted into the corresponding chiral allenes in high yields and with high enantiomeric purities (Table 2).

Table 1. Reaction of 1-decyne (**9a**) and aldehyde (**10a**) with piperazine **5**, promoted by zinc halides.[a].



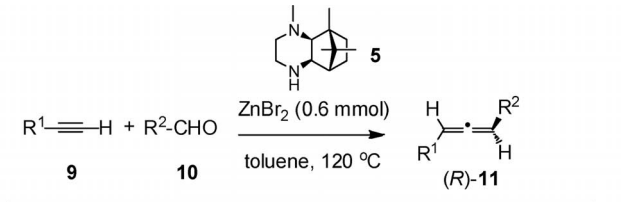
Entry	Zinc halide	mmol	Time [h]	Yield [%][b]	*ee* [%][c]
1	$ZnCl_2$	1	4	28	99
2	$ZnCl_2$	0.8	4	17	99
3	$ZnCl_2$	0.6	6	11	99
3	$ZnBr_2$	1	4	71	91
4	$ZnBr_2$	0.8	4	69	94
5	$ZnBr_2$	0.6	6	65	98
6	ZnI_2	1	4	54	87
7	ZnI_2	0.8	4	68	90
8	ZnI_2	0.6	4	61	96

[a] The reactions were carried out by taking piperazine **5** (1.0 mmol), benzaldehyde (1 mmol), and 1-decyne (1.1 mmol) in toluene (3 mL) at 25 °C. [b] Isolated yields. [c] The *ee* was determined by HPLC analysis.

Substituted benzaldehydes reacted with 1-decyne to give the corresponding chiral allenes (i.e., **11aa**–**11ah**) in 58–75% yield, and with up to 90–99% *ee* (Table 2). The reaction between benzaldehyde (**10a**) and phenylacetylene (**9b**) gave **11ba** in 42% yield and with 79% *ee* (Table 2). 1-Phenylbutyne (**9c**) reacted with benzaldehyde (**10a**) to give the corresponding allene **11ca** in 72% yield, and with 98% *ee* (Table 2). The reaction was also applicable to aliphatic alkynes, as illustrated by the reactions of alkynes **9d**, **9e**, and **9f** with benzaldehyde. The corresponding chiral allenes (i.e., **11da**, **11ea,** and **11fa**) were obtained in 62–68% yield, and with 79–99% *ee* (Table 2). We observed that the reaction of simple propargyl alcohol with benzaldehyde under these

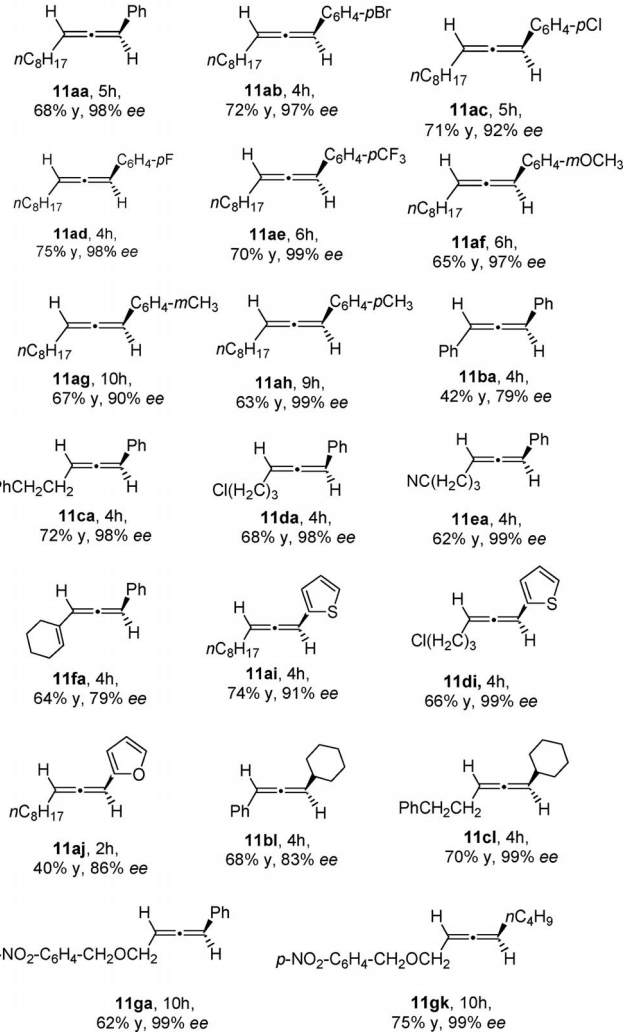
reaction conditions led only to a complex mixture of products, whereas protected forms of propargyl alcohol, such as its *p*-nitrobenzyl ether derivative **9g**, react with aldehydes like **10a** and **10k** to give the corresponding chiral allenes (i.e., **11ga** and **11gk**) in 62–75% yield, and with up to 99%

Table 2. Reaction of terminal alkynes **9** and aldehydes **10** with chiral piperazine **5**, promoted by zinc bromide.[a,b,c]



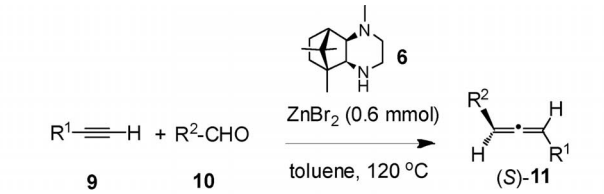
9 **10**

R^1	R^2	R^2
9a: *n*-C_8H_{17}	**10a**: Ph	**10h**: C_6H_4-*p*-CH_3
9b: Ph	**10b**: C_6H_4-*p*-Br	**10i**: 2-thiophenyl
9c: $PhCH_2CH_2$	**10c**: C_6H_4-*p*-Cl	**10j**: 2-furanyl
9d: $Cl(CH_2)_3$	**10d**: C_6H_4-*p*-F	**10k**: *n*-C_4H_9
9e: $NC(CH_2)_3$	**10e**: C_6H_4-*p*-CF_3	**10l**: *c*-hexyl
9f: *c*-hexenyl	**10f**: C_6H_4-*m*-OCH_3	
9g: *p*-NO_2-C_6H_4-CH_2OCH_2	**10g**: C_6H_4-*m*-CH_3	



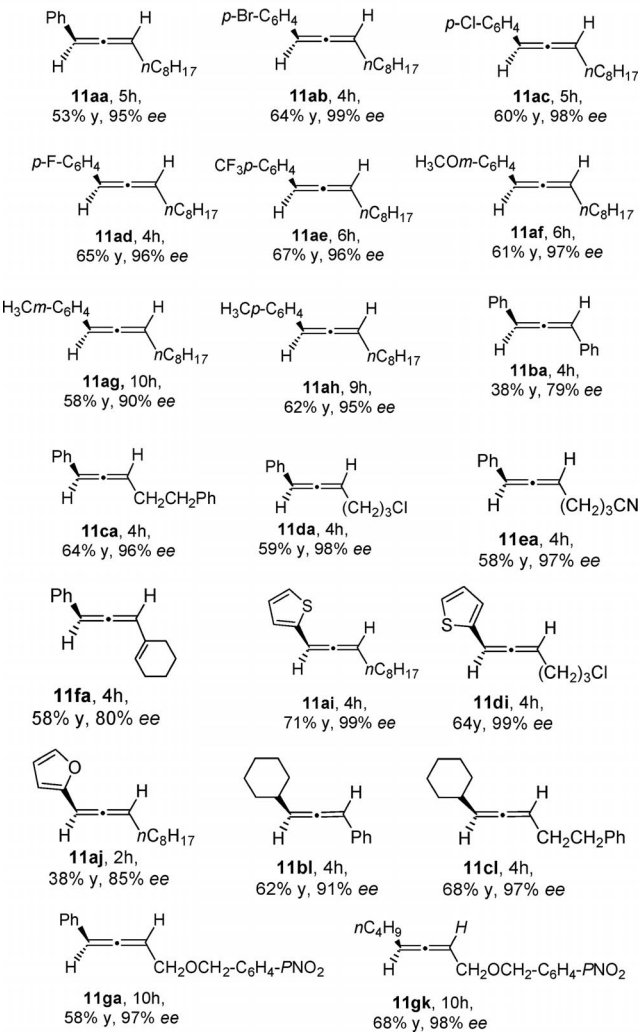
[a] The reactions were carried out by taking piperazine **5** (1.0 mmol), $ZnBr_2$ (0.6 mmol), aldehyde (1 mmol), and 1-alkyne (1.1 mmol) in toluene (3 mL) at 25 °C. [b] Isolated yields. [c] The *ee* value was determined by HPLC analysis.

Table 3. Reaction of terminal alkynes **9** and aldehydes **10** with chiral piperazine **6**, promoted by zinc bromide.[a,b,c]



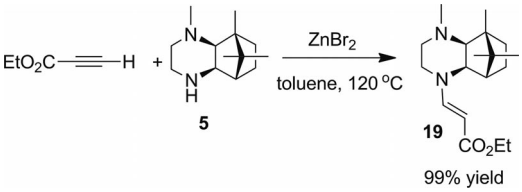
9 **10**

R^1	R^2	R^2
9a: *n*-C_8H_{17}	**10a**: Ph	**10h**: C_6H_4-*p*-CH_3
9b: Ph	**10b**: C_6H_4-*p*-Br	**10i**: 2-thiophenyl
9c: $PhCH_2CH_2$	**10c**: C_6H_4-*p*-Cl	**10j**: 2-furanyl
9d: $Cl(CH_2)_3$	**10d**: C_6H_4-*p*-F	**10k**: *n*-C_4H_9
9e: $NC(CH_2)_3$	**10e**: C_6H_4-*p*-CF_3	**10l**: *c*-hexyl
9f: *c*-hexenyl	**10f**: C_6H_4-*m*-OCH_3	
9g: *p*-NO_2-C_6H_4-CH_2OCH_2	**10g**: C_6H_4-*m*-CH_3	



[a] The reactions were carried out by taking piperazine **6** (1.0 mmol), $ZnBr_2$ (0.6 mmol), aldehyde (1 mmol), and 1-alkyne (1.1 mmol) in toluene (3 mL) at 25 °C. [b] Isolated yields. [c] The *ee* was determined by HPLC analysis.

ee (Table 2). Thiophene-2-aldehyde (**10i**) also reacted with 1-alkynes **9a** and **9d** to give the corresponding allenes (i.e., **11ai** and **11di**) in reasonable yields and with reasonable selectivity (Table 2). However, we observed that the reaction of ethyl propiolate with chiral piperazine **5** gave the corresponding Michael addition product (i.e., **19**; Scheme 8).



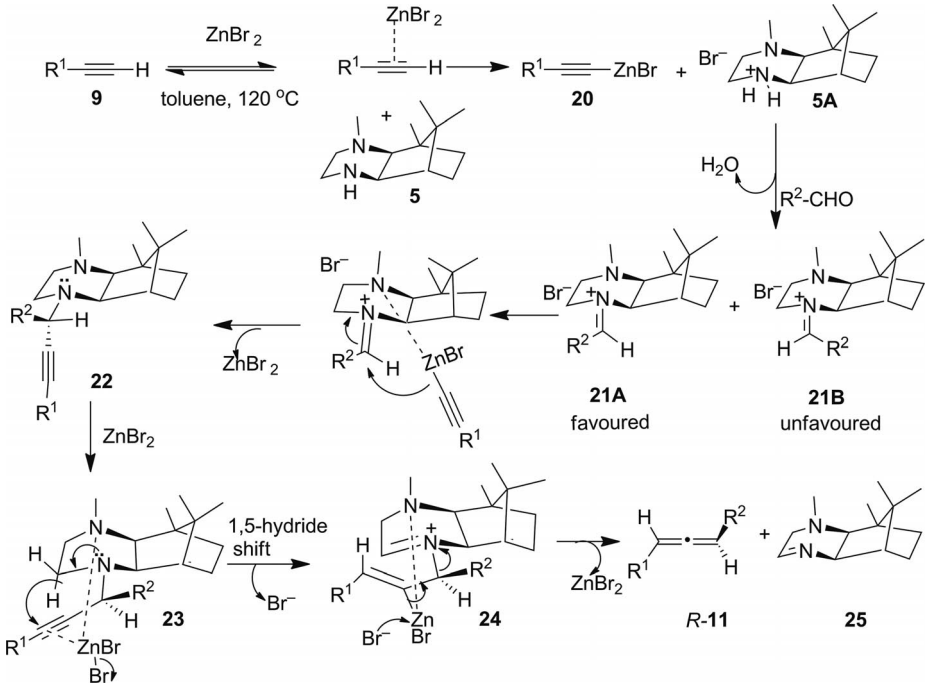
Scheme 8. Formation of Michael addition product **19** in the reaction of ethyl propiolate with chiral piperazine **5**.

All the optically active allenes obtained using **5** were levorotatory, from which the absolute configurations of the major enantiomers of the allenes were assigned as (*R*) by the Lowe–Brewster rule, and also by comparison with reported $[\alpha]_D^{25}$ values.[8] The formation of chiral allenes in this transformation can be explained by considering the mechanism outlined in (Scheme 9). Previously, the formation of an alkynylzinc intermediate was reported in the reaction of 1-alkyne, triethylamine, and zinc triflate.[9a] Also, alkynylzinc addition to iminium ion intermediates has been reported.[9b] Accordingly, initially formed alkynylzinc intermediate **20** would react with favoured conformer **21A** of the iminium ion derived from aldehyde **10** and chiral piperazine **5** to selectively give the corresponding propargylamine (i.e., **22**; Scheme 9). Thus, the formation of the single isomer of intermediate **22** is mainly due to the exclusive formation of the favoured conformer of iminium ion intermediate **21A** prior to the addition of the alkynlzinc reagent, which is directed by coordination to the other nitrogen. The corresponding zinc bromide complex of propargylamine intermediate **23** would then undergo an intramolecular hydride shift to give alkenylzinc intermediate **24**, which would then undergo elimination of zinc bromide and the imine by antiperiplanar cleavage of the C–N bond in intermediate **24** to give chiral allene (*R*)-**11** and the corresponding chiral camphanyl imine (i.e., **25**). Such hydrogen shifts were previously considered in the gold- and silver-catalysed transformation of propargylamine derivatives into chiral allenes.[4a,4b]

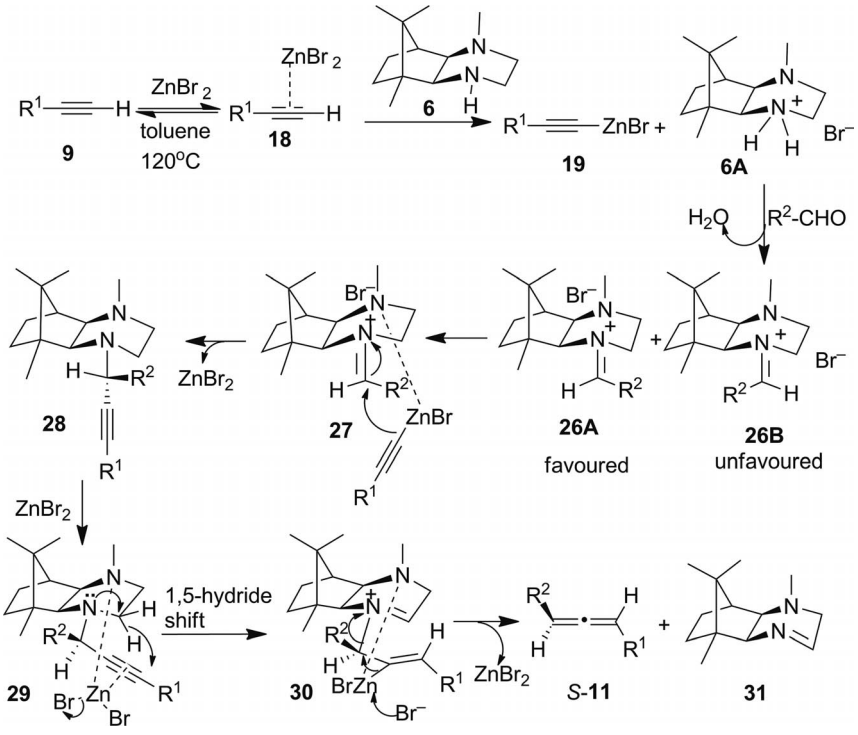
We found that imine by-product **25** could easily be converted into starting chiral piperazine **5** by simple borohydride reduction without any change in enantiomeric purity.

We then examined the use of isomeric piperazine **6** in chiral allene synthesis. We observed that the reaction of 1-decyne (**9a**), benzaldehyde (**10a**), and piperazine **6** using $ZnBr_2$ (0.6 mmol) led to the (*S*)-allene in 53% yield, and with 95% *ee*, with reversed enantioselectivity, as expected (Table 3). This transformation is also generally applicable to different aldehydes and 1-alkynes. The corresponding chiral 1,3-disubstituted allenes were obtained in 38–71% yields with high enantioselectivities 79–99% (Table 3). Again, all the optically active allenes obtained using **6** were dextrorotatory, from which the absolute configurations of the major enantiomers of the chiral allenes were assigned as (*S*) by the Lowe–Brewster rule, and also by comparison with reported $[\alpha]_D^{25}$ values.

The formation of chiral (*S*)-allenes using **6** can be explained by considering a mechanism outlined in (Scheme 10). In this case, favoured iminium ion intermediate **26A** would lead to propargylamine intermediate **28**, which has an (*R*) configuration at the newly formed ste-



Scheme 9. Mechanism for the formation of (*R*)-allenes using piperazine **5**.



Scheme 10. Mechanism for the formation of (*S*)-allenes using piperazine **6**.

reogenic centre, in contrast to (*S*)-propargylamine intermediate **18**, which was formed using regioisomeric chiral piperazine **5**. Thus, the corresponding zinc bromide complex of **29** is expected to undergo an intramolecular hydride shift from the camphanyl skeleton to the acetylinic moiety to give alkenylzinc intermediate **30**, which, after cleavage of the C–N bond via an antiperiplanar transition state, would result in the formation of the (*S*)-allene, along with zinc bromide and chiral camphanyl imine **31**.

Conclusions

In summary, we have developed a versatile and efficient stereoselective synthesis of both enantiomers of several chiral 1,3-disubstituted allenes with high enantiomeric purities, exploiting the chiral discrimination abilities of the regioisomers of chiral *N*-methyl-substituted camphanyl-piperazine derivatives **5** and **6** in a $ZnBr_2$-promoted transformation. Since chiral piperazine derivatives **5** and **6** are readily accessible, and are also easily recoverable for reuse without loss in optical purity, the method described here has considerable potential for further synthetic exploitation.

Experimental Section

General Information: Melting points were determined using a Superfit capillary melting point apparatus. IR (KBr) spectra were recorded with a JASCO FTIR spectrophotometer Model 5300. Neat IR spectra were recorded with a JASCO FTIR spectrophotometer Model 5300 or a SHIMADZU FTIR spectrophotometer Model 8300, with polystyrene as reference. ^1H (400 MHz) and ^{13}C (100 MHz) NMR spectra were recorded with Bruker AC 200 and Bruker Avance 400 spectrometers, respectively with $CDCl_3$ as solvent and tetramethylsilane (TMS) as reference (δ = 0 ppm). Chemical shifts are expressed in δ downfield from the signal of TMS. Liquid chromatography (LC) and mass analysis (LC-MS) were performed with a SHIMADZU-LCMS-2010A instrument. The mass spectral analyses were carried out using the chemical ionization (CI) or electrospray ionization (ESI) techniques. Elemental analyses were carried out using a Perkin–Elmer elemental analyser model-240C or a Thermo Finnigan analyser series Flash EA 1112. Mass spectral analyses for some of the compounds were carried out with a VG 7070H mass spectrometer using the EI technique at 70 eV. Optical rotations were measured with Rudolph Research Analytical AUTOPOL-II (readability ±0.01°) and AUTOPOL-IV (readability ±0.001°) automatic polarimeters. The condition of the polarimeter was checked by measuring the optical rotation of a standard *S*-(–)-diphenyl prolinol, 99% *ee* (DPP), which was purchased from Gerchem Labs (P) Ltd., Hyderabad. Analytical grade $ZnCl_2$ and $ZnBr_2$ were purchased from E. Merck, India, and Nice Chemicals Pvt Ltd., India, respectively. ZnI_2 was purchased from Sigma–Aldrich. Powdered zinc halide samples were heated at 120 °C under reduced pressure (0.001 Torr) in a vacuum oven and stored under dry nitrogen. Toluene supplied by E. Merck, India, was freshly distilled from sodium benzophenone ketyl before use. Analytical thin layer chromatography was carried out on glass-backed plates (3 × 10 cm) coated with 250 μm Acme silica gel-G and GF_{254} containing 13% calcium sulfate as binder. The spots were visualized by short exposure to iodine vapor or UV light. Column chromatography was carried out using Acme silica gel (100–200 or 230–400 mesh) or neutral alumina.

***tert*-Butyl 5,9,9-Trimethyloctahydro-5,8-methanoquinzoline-1-carboxylate (16):** $(Boc)_2O$ (1.090 g, 5 mmol) in dry CH_2Cl_2 (10 mL) was added carefully over a period of 0.5 h to a stirred solution of piperazine **4** (1.940 g, 10 mmol) in dry CH_2Cl_2 (20 mL) at 0 °C, and the

resulting mixture was stirred for a further 12 h at 25 °C. The CH_2Cl_2 was removed under reduced pressure, and amide **16** (2.513 g, 85%) was isolated by column chromatography on silica gel 100–200 (hexane/ethyl acetate, 1:1 as eluent). $[\alpha]_D^{25}$ = –68.2 (*c* = 0.55, $CHCl_3$). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 3.56–3.53 (d, 1 H), 3.44–3.41 (d, 1 H), 3.18–3.17 (t, 1 H), 3.03–2.96 (m, 2 H), 2.67–2.63 (m, 1 H), 2.06 (s, 1 H), 1.67–1.65 (m, 1 H), 1.53–1.52 (m, 1 H), 1.47 (s, 9 H), 1.15 (s, 3 H), 1.13 (s, 3 H), 1.12 (s, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 156.2, 79.3, 66.1, 58.7, 48.4, 45.5, 43.0, 35.5, 28.5, 26.6, 22.0, 21.3, 11.6 ppm. IR (neat): $\tilde{\nu}$ = 3335, 2953, 1689, 1369, 1172, 1032, 777 cm^{-1}. LCMS: *m*/*z* = 295 [M + 1]. $C_{17}H_{30}N_2O_2$ (294.44): calcd. C 69.35, H 10.27, N 9.51; found C 69.21, H 10.35, N 9.45.

***tert*-Butyl 4,5,9,9-Trimethyloctahydro-5,8-methanoquinzoline-1-carboxylate (17):** CH_3I (2.100 g, 15 mmol) in dry THF (10 mL) was added carefully to a stirred solution of amide **16** (2.941 g, 10 mmol) and NaH (0.360 g, 15 mmol) in dry THF (20 mL) at 0 °C, and the resulting solution was stirred for a further 2 h at 25 °C. Water (5 mL) was added, followed by diethyl ether (30 mL). The diethyl ether layer was separated, washed with NaCl (saturated aq.), dried (Na_2SO_4), and concentrated. Amine **17** (2.799 g, 90%) was isolated by column chromatography on silica gel 100–200 (hexane/ethyl acetate, 9:1 as eluent). $[\alpha]_D^{25}$ = –61.2 (*c* = 0.52, $CHCl_3$). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 3.69–3.60 (m, 2 H), 3.35–3.32 (m, 1 H), 2.67–2.65 (m, 1 H), 2.24 (s, 3 H), 1.87 (s, 1 H), 1.67 (s, 1 H), 1.45 (s, 9 H), 1.04 (s, 5 H), 0.99 (s, 3 H), 0.77 (s, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 156.0, 79.4, 74.8, 59.0, 54.5, 53.3, 49.8, 48.5, 45.6, 41.8, 36.2, 28.5, 26.6, 22.1, 20.4, 14.6 ppm. IR (neat): $\tilde{\nu}$ = 2953, 1695, 1454, 1367, 1170, 869, 775 cm^{-1}. LCMS: *m*/*z* = 309 [M + 1]. $C_{18}H_{32}N_2O_2$ (308.46): calcd. C 70.09, H 10.46, N 9.08; found C 70.21, H 10.35, N 9.16.

1,8,9,9-Tetramethyldecahydro-5,8-methanoquinazoline (5): CF_3COOH (5 mL) was added carefully to a stirred solution of amide **17** (3.900 g, 10 mmol) in dry CH_2Cl_2 (10 mL) at 0 °C, and the resulting solution was stirred for a further 12 h at 25 °C. The CF_3COOH (5 mL) was removed under reduced pressure, and $NaHCO_3$ (saturated aq.; 10 mL) and CH_2Cl_2 (25 mL) were added. The CH_2Cl_2 layer was separated, washed with NaCl (saturated aq.), dried (Na_2SO_4), and concentrated. Piperazine **5** (1.943 g, 93%) was isolated by column chromatography on silica gel 100–200 (chloroform/methanol, 9:1 as eluent). $[\alpha]_D^{25}$ = +22.7 (*c* = 0.53, $CHCl_3$). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 3.12–3.09 (m, 1 H), 2.77–2.73 (m, 2 H), 2.64–2.58 (m, 1 H), 2.25 (s, 3 H), 1.91–1.63 (m, 6 H), 1.41 (s, 3 H), 1.25–1.11 (m, 3 H), 1.06 (s, 3 H), 0.83 (s, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 79.8, 61.6, 54.9, 50.3, 50.0, 47.2, 46.1, 41.9, 37.4, 27.2, 22.2, 21.0, 15.8 ppm. IR (neat): $\tilde{\nu}$ = 3281, 3076, 2934, 1554, 1485, 1415, 1379, 1147, 1055, 808, 692 cm^{-1}. LCMS: *m*/*z* = 209 [M + 1]. $C_{13}H_{24}N_2$ (208.34): calcd. C 74.94, H 11.61, N 13.45; found C 74.85, H 11.56, N 13.56.

1,8,9,9-Tetramethyldecahydro-5,8-methanoquinazoine (6):

An oven-dried 100 mL reaction flask was flushed with dry nitrogen, and *t*BuOK (1.940 g, 10 mmol) and dry THF (20 mL) were added. The mixture was cooled to –78 °C, and then piperazine **4** (1.94 g, 10 mmol) in dry THF (10 mL) was added. The resulting mixture was stirred for 0.5 h at –78 °C. MeI (0.66 mL, 10 mmol) in dry THF (5 mL) was then added to this reaction mixture. After about 15 min, the reaction was quenched with water, and diethyl ether was added. The separated organic phase was washed with NaCl solution and dried with Na_2SO_4. Purification by column chromatography (basic alumina) in hexane gave optically pure piperazine **6** (1.773 g, 85%). $[\alpha]_D^{25}$ = –24.6 (*c* = 0.45, $CHCl_3$). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 3.13–3.08 (m, 1 H), 2.68–2.61 (m, 2 H), 2.54–2.52 (d, *J* = 8.0 Hz, 1 H), 2.17 (s, 3 H), 1.90–1.89 (d, *J* = 4.0 Hz, 1 H), 1.75–1.65 (m, 4 H), 1.54–1.47 (m, 2 H), 1.36 (s, 3 H), 1.19–1.11 (m, 3 H), 0.95 (s, 3 H), 0.81 (s, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 74.5, 67.1, 52.6, 47.7, 46.9, 46.5, 43.0, 41.8, 36.5, 26.5, 22.6, 20.3, 12.0 ppm. IR (neat): $\tilde{\nu}$ = 3281, 3076, 2934, 1554, 1485, 1415, 1379, 1147 cm^{-1}. HRMS (ESI): calcd. for $C_{13}H_{25}N_2$ [M + H]$^+$ 209.2118; found 209.2131.

1,4-Bis(1,3-diphenylprop-2-ynyl)-5,9,9-trimethyldecahydro-5,8-methanoquinazoline (15): A stirred suspension of piperazine **4** (0.194 g, 1 mmol), $ZnCl_2$ (0.010 g 0.1 mmol), and phenylacetylene **9b** (0.102 g, 1 mmol) in toluene (3 mL) was heated to 120 °C for 15 min. Freshly distilled benzaldehyde **10a** (0.110 g, 1 mmol) was added at 25 °C, and then the resulting mixture was heated at reflux at 120 °C under a nitrogen atmosphere. The reaction mixture was brought to room temperature after 4 h. The toluene was removed, water (5 mL) was added, and the mixture was extracted with CH_2Cl_2 (25 mL). The CH_2Cl_2 phase was separated, dried with anhydrous Na_2SO_4, filtered, and concentrated under reduced pressure. The crude product was purified by column chromatography on silica gel 100–200 (hexane/ethyl acetate, 95:5 as eluent) to give optically pure amine **15** (0.533 g, 93%). $[\alpha]_D^{25}$ = +43 (*c* = 1.62, $CHCl_3$). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.79–7.74 (t, *J* = 20.0 Hz, 4 H), 7.52–7.48 (t, *J* = 16.0 Hz, 4 H), 7.40–7.26 (m, 10 H), 7.21–7.17 (t, *J* = 16 Hz, 2 H), 5.24 (s, 1 H), 5.04 (s, 1 H), 3.46–3.38 (m, 2 H), 2.93–2.85 (m, 1 H), 2.70–2.64 (m, 2 H), 2.33–2.28 (m, 2 H), 1.89–1.82 (m, 1 H), 1.59 (s, 3 H), 1.38–1.28 (m, 2 H), 1.15 (s, 3 H), 0.98 (s, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 139.6, 139.4, 131.9, 131.8, 128.3, 128.3, 128.2, 128.1, 128.0, 127.9, 127.3, 123.3, 123.2, 88.9, 88.5, 85.2, 85.0, 68.6, 67.3, 62.4, 58.4, 51.2, 48.1, 47.1, 45.8, 44.0, 36.1, 26.6, 22.2, 20.8, 13.6 ppm. IR (neat): $\tilde{\nu}$ = 3076, 2934, 1554, 1485, 1415, 1379, 1147 cm^{-1}. LCMS: *m*/*z* = 575 [M + 1]. $C_{42}H_{42}N_2$ (574.81): calcd. C 87.76, H 7.36, N 4.87; found C 87.58, H 7.41, N 4.79.

1-(1,3-Diphenylprop-2-ynyl)-4,5,9,9-Tetramethyldecahydro-5,8-methanoquinazoline (18): A stirred suspension of piperazine **5** (0.208 g, 1 mmol), $ZnCl_2$ (0.010 g, 0.1 mmol), and phenylacetylene **9b** (0.102 g, 1 mmol) in toluene (3 mL) was heated to 120 °C for 15 min. Freshly distilled benzaldehyde **10a** (0.110 g, 1 mmol) was added at 25 °C, and the resulting mixture was heated at reflux at 120 °C under a nitrogen atmosphere. The reaction mixture was brought to room temperature after 4 h. The toluene was removed, water (5 mL) was added, and the mixture was extracted with CH_2Cl_2 (25 mL). The CH_2Cl_2 phase was separated, dried with anhydrous Na_2SO_4, filtered, and concentrated under reduced pressure. The crude product was purified by column chromatography on silica gel 100–200 (hexane/ethyl acetate, 95:5 as eluent) to give optically pure piperazine **18** (0.358 g, 90%). $[\alpha]_D^{25}$ = –74.7 (*c* = 0.52, $CHCl_3$). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.70–7.68 (d, *J* = 8 Hz, 2 H), 7.56–7.54 (d, *J* = 8 Hz, 2 H), 7.38–7.26 (m, 6 H), 5.25 (s, 1 H), 3.15–3.12 (d, *J* = 12 Hz, 1 H), 2.59–2.57 (m, 1 H), 2.49–2.48 (m, 1 H), 2.26–1.23 (m, 5 H), 1.99–1.63 (m, 1 H), 1.52 (s, 3 H), 1.30–1.25 (m, 3 H), 1.06 (s, 3 H), 0.83 (s, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 138.9, 132.0, 128.3, 128.2, 127.2, 123.3, 87.8, 86.0, 78.1, 65.6, 58.2, 54.2, 50.3, 48.2, 47.5, 47.4, 42.9, 37.2, 26.3, 22.2, 21.2, 14.7 ppm. IR (neat): $\tilde{\nu}$ = 3061, 3026, 2951, 2870, 2831, 2756, 1599, 1489, 1488, 1388, 1365, 1064 842, 694 cm^{-1}. LCMS: *m*/*z* = 399 [M + 1]. $C_{28}H_{34}N_2$ (398.58): calcd. C 84.31, H 8.60, N 7.03; found C 84.21, H 8.51, N 7.12.

Reaction of Terminal Alkyne, Aldehyde, and Amine with $ZnBr_2$: Amine (**5** or **6**; 0.209 g, 1 mmol) was dissolved in toluene (3 mL) in a flame-dried 25 mL reaction flask, and $ZnBr_2$ (0.135 g, 0.6 mmol) and alkyne **9** (1.1 mmol) were added. The mixture was

stirred in a pre-heated oil bath at 120 °C for 10 min. The reaction flask was then removed from the oil bath and cooled to room temperature under nitrogen. Freshly distilled aldehyde **10** (1 mmol) was added to the reaction mixture at 25 °C. The resulting mixture was gradually heated to 120 °C over about 45 min, and was stirred for the time given in Table 2 or 3. The mixture was brought to 25 °C, the toluene was evaporated, the residue was purified by column chromatography on silica gel (100–200 mesh) using hexane as eluent to give the chiral allene.

1-Phenylundeca-1,2-diene (11aa): Data for (*R*)-**11aa**: Yield 0.155 g (68%); 98% *ee.* $[\alpha]_D^{25}$ = –225.2 (*c* = 0.50, $CHCl_3$). Data for (*S*)-**11aa**: Yield 0.120 g (53%); 95% *ee.* $[\alpha]_D^{25}$ = +215.7 (*c* = 0.50, $CHCl_3$). HPLC using chiral column, chiralcel OD-H; hexanes/*i*PrOH, 100:0; flow rate 1.5 mL/min; 254 nm; retention times: 4.7 min (*R*) and 5.2 min (*S*). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.34–7.28 (m, 4 H), 7.24–7.20 (m, 1 H), 6.19–6.14 (m, 1 H), 5.64–5.58 (m, 1 H), 2.19–2.15 (m, 2 H), 1.56–1.51 (m, 2 H), 1.41–1.32 (m, 12 H), 0.95–0.91 (t, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 14.1, 22.6, 28.7, 29.1, 29.3, 29.4, 31.8, 94.5, 95.5, 126.5, 128.5, 135.1, 205.1 ppm. The ^{13}C NMR spectroscopic data was in agreement with the reported data, see ref.[6] IR (neat): $\tilde{\nu}$ = 2926, 2854, 1950, 1599, 1460, 773 cm^{-1}.

1-(4-Bromophenyl)undeca-1,2-diene (11ab): Data for (*R*)-**11ab**: Yield 0.220 g (72%); 97% *ee.* $[\alpha]_D^{25}$ = –148.4 (*c* = 0.50, $CHCl_3$). Data for (*S*)-**11ab**: Yield 0.196 g (64%); 99% *ee.* $[\alpha]_D^{25}$ = +154.7 (*c* = 0.50, $CHCl_3$). HPLC using chiral column, chiralcel OD-H; hexanes/*i*PrOH, 100:0; flow rate 1.5 mL/min; 254 nm; retention times: 3.5 min (*S*) and 4.6 min (*R*). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.44–7.41 (d, 2 H), 7.18–7.15 (d, 2 H), 6.10–6.07 (m, 1 H), 5.61–5.56 (m, 1 H), 2.17–2.11 (m, 2 H), 1.51–1.46 (m, 2 H), 1.39–1.28 (m, 10 H), 0.92–0.89 (t, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 205.2, 134.2, 131.6, 128.0, 120.1, 95.5 93.7, 31.8, 29.3, 29.3, 29.1, 29.1, 28.6, 22.6, 14.1 ppm. The ^{13}C NMR spectroscopic data was in agreement with the reported data, see ref.[6] IR (neat): $\tilde{\nu}$ = 2926, 2858, 1950, 1599, 1487, 829 cm^{-1}.

1-(4-Chlorophenyl)undeca-1,2-diene (11ac): Data for (*R*)-**11ac**: Yield 0.190 g (71%); 92% *ee.* $[\alpha]_D^{25}$ = –163.6 (*c* = 0.50, $CHCl_3$). Data for (*S*)-**11ac**: Yield 0.162 g (60%); 98% *ee.* $[\alpha]_D^{25}$ = +172.9 (*c* = 0.50, $CHCl_3$). HPLC using chiral column, chiralcel OD-H; hexanes/*i*PrOH, 100:0; flow rate 1.5 mL/min; 254 nm; retention times: 3.3 min (*S*) and 4.2 min (*R*). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.27–7.20 (m, 4 H), 6.09–6.06 (m, 1 H), 5.60–5.55 (m, 1 H), 2.16–2.09 (m, 2 H), 1.51–1.44 (m, 2 H), 1.37–1.26 (m, 10 H), 0.92–0.87 (t, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 205.2, 133.7, 132.1, 128.6, 127.7, 95.5, 93.7, 31.8, 29.3, 29.3, 29.1, 28.6, 22.6, 14.1 ppm. The ^{13}C NMR spectroscopic data was in agreement with the reported data, see ref.[6] IR (neat): $\tilde{\nu}$ = 2926, 2854, 1950, 1491, 831 cm^{-1}.

1-(4-Fluorophenyl)undeca-1,2-diene (11ad): Data for (*R*)-**11ad**: Yield 0.175 g (75%); 98% *ee.* $[\alpha]_D^{25}$ = –162.7 (*c* = 0.45, $CHCl_3$). Data for (*S*)-**11ad**: Yield 0.150 g (65%); 96% *ee.* $[\alpha]_D^{25}$ = +157.3 (*c* = 0.45, $CHCl_3$). HPLC using chiral column, chiralcel OD-H; hexanes/*i*PrOH, 100:0; flow rate 1.5 mL/min; 254 nm; retention times: 4.4 min (*S*) and 4.8 min (*R*). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.26–7.22 (m, 2 H), 7.01–6.96 (m, 2 H), 6.11–6.08 (m, 1 H), 5.57–5.56 (m, 1 H), 2.15–2.09 (m, 2 H), 1.50–1.44 (m, 2 H), 1.37–1.28 (m, 10 H), 0.98–0.89 (t, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 204.9, 162.9, 160.5, 131.1, 127.9, 127.8, 115.5, 115.3, 95.3, 93.9, 31.8, 29.4, 29.3, 29.2, 29.1, 28.7, 22.6, 14.1 ppm. The ^{13}C NMR spectroscopic data was in agreement with the reported data, see ref.[6] IR (neat): $\tilde{\nu}$ = 2926, 2854, 1950, 1602, 1508, 1228, 837 cm^{-1}.

1-(4-Trifluoromethyl)phenylundeca-1,2-diene (11ae): Data for (*R*)-**11ae**: Yield 0.210 g (70%); 99% *ee.* $[\alpha]_D^{25}$ = –175.6 (*c* = 0.60, $CHCl_3$). Data for (*S*)-**11ae**: Yield 0.201 g (67%); 96% *ee.* $[\alpha]_D^{25}$ = +169.2 (*c* = 0.60, $CHCl_3$). HPLC using chiral column, chiralcel OD-H; hexanes/*i*PrOH, 100:0; flow rate 1.5 mL/min; 254 nm; retention times: 15.4 min (*S*) and 17.0 min (*R*). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.55–7.52 (d, *J* = 12 Hz, 2 H), 7.38–7.36 (d, *J* = 8 Hz, 2 H), 6.16–6.13 (m, 1 H), 5.66–5.62 (m, 1 H), 2.18–2.12 (m, 2 H), 1.54–1.45 (m, 2 H), 1.38–1.27 (m, 10 H), 0.89–0.88 (t, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 206.1, 139.1, 131.6, 126.6, 125.6, 125.4, 125.4, 95.6, 93.8, 31.8, 29.3, 29.2, 29.1, 29.0, 28.5, 22.6, 14.0 ppm. The ^{13}C NMR spectroscopic data was in agreement with the reported data, see ref.[6] IR (neat): $\tilde{\nu}$ = 2928, 2856, 1950, 1616, 1325, 844 cm^{-1}.

1-(3-Methoxyphenyl)undeca-1,2-diene (11af): Data for (*R*)-**11af**: Yield 0.167 g (65%); 97% *ee.* $[\alpha]_D^{25}$ = –201.7 (*c* = 0.50, $CHCl_3$). Data for (*S*)-**11af**: Yield 0.157 g (61%); 97% *ee.* $[\alpha]_D^{25}$ = +201.2 (*c* = 0.50, $CHCl_3$). HPLC using chiral column, chiralcel OJ-H; hexanes/*i*PrOH, 100:0; flow rate 1.0 mL/min; 254 nm; retention times: 7.3 min (*R*) and 9.5 min (*S*). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.24–7.20 (m, 1 H), 6.90–6.86 (m, 2 H), 6.76–6.74 (m, 1 H), 6.12–6.10 (m, 1 H), 5.58–5.57 (m, 1 H), 3.81 (s, 3 H), 2.17–2.12 (m, 2 H), 1.53–1.46 (m, 2 H), 1.39–1.28 (m, 10 H), 0.91–0.87 (t, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 205.2, 159.8, 136.7, 129.4, 119.3, 112.4, 111.7, 95.2, 94.5, 55.1, 31.8, 29.4, 29.3, 29.2, 28.7, 22.6, 14.1 ppm. The ^{13}C NMR spectroscopic data was in agreement with the reported data, see ref.[6] IR (neat): $\tilde{\nu}$ = 3055, 2926, 2854, 1946, 1508, 1325, 817, 746 cm^{-1}.

1-(3-Methylphenyl)undeca-1,2-diene (11ag): Data for (*R*)-**11ag**: Yield 0.163 g (67%); 90% *ee.* $[\alpha]_D^{25}$ = –125.5 (*c* = 0.55, $CHCl_3$). Data for (*S*)-**11ag**: Yield 0.140 g (58%); 90% *ee.* $[\alpha]_D^{25}$ = +125.1 (*c* = 0.55, $CHCl_3$). HPLC using chiral column, chiralcel OJ-H; hexanes/*i*PrOH, 100:0; flow rate 1.0 mL/min; 254 nm; retention times: 5.8 min (*R*) and 8.3 min (*S*). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.28–7.22 (m, 1 H), 7.16–7.14 (d, *J* = 8 Hz, 2 H), 7.05–7.04 (d, *J* = 4.0 Hz, 1 H), 6.16–6.13 (m, 1 H), 5.62–5.57 (m, 1 H), 2.38 (s, 3 H), 2.20–2.15 (m, 2 H), 1.56–1.52 (m, 2 H), 1.43–1.32 (m, 10 H), 0.94–0.92 (t, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 205.1, 138.1, 135.0, 128.4, 127.4, 127.2, 123.7, 94.9, 94.5, 31.9, 29.4, 29.3, 29.2, 28.8, 22.7, 21.4, 14.1 ppm. The ^{13}C NMR spectroscopic data was in agreement with the reported data, see ref.[6] IR (neat): $\tilde{\nu}$ = 2957, 2926, 1950, 1599, 1494, 690 cm^{-1}.

1-(4-Methylphenyl)undeca-1,2-diene (11ah): Data for (*R*)-**11ah**: Yield 0.152 g (63%); 99% *ee.* $[\alpha]_D^{25}$ = –172.2 (*c* = 0.55, $CHCl_3$). Data for (*S*)-**11ah**: Yield 0.150 g (62%); 95% *ee.* $[\alpha]_D^{25}$ = +164.9 (*c* = 0.55, $CHCl_3$). HPLC using chiral column, chiralcel OJ-H; heptane/*i*PrOH, 100:0; flow rate 1.5 mL/min; 254 nm; retention times 4.9 min (*R*) and 5.5 min (*S*). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.20–7.18 (d, *J* = 8 Hz, 2 H), 7.12–7.10 (d, *J* = 8 Hz, 2 H), 6.12–6.09 (m, 1 H), 5.55–5.54 (m, 1 H), 2.36 (s, 3 H), 2.15–2.10 (m, 2 H), 1.50–1.44 (m, 2 H), 1.38–1.27 (m, 10 H), 0.94–0.90 (t, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 204.8, 136.3, 132.1, 129.2, 126.4, 95.0, 94.3, 31.8, 29.4, 29.3, 29.2, 28.8, 22.7, 21.1, 14.1 ppm. The ^{13}C NMR spectroscopic data was in agreement with the reported data, see ref.[6] IR (neat): $\tilde{\nu}$ = 2924, 2854, 1948, 1512, 1464, 821 cm^{-1}.

1,5-Diphenylpenta-1,2-diene (11ca): Data for (*R*)-**11ca**: Yield 0.159 g (72%); 98% *ee.* $[\alpha]_D^{25}$ = –210.1 (*c* = 0.45, $CHCl_3$). Data for (*S*)-**11ca**: Yield 0.143 g (64%); 96% *ee.* $[\alpha]_D^{25}$ = +206.9 (*c* = 0.45, $CHCl_3$). HPLC using chiral column, chiralcel OD-H; hexanes/*i*PrOH, 100:0; flow rate 1.5 mL/min; 254 nm; retention times: 9.6 min (*R*) and 11.1 min (*S*). ^{1}H NMR (400 MHz, $CDCl_3$): δ =

7.31–7.28 (m, 4 H), 7.25–7.16 (m, 6 H), 6.14–6.11 (d, J = 8 Hz, 1 H), 5.62–5.57 (m, 1 H), 2.84–2.79 (m, 2 H), 2.51–2.43 (m, 2 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 205.3, 141.5, 134.8, 128.6, 128.5, 128.4, 126.7, 126.6, 125.9, 95.0, 94.3, 35.4, 30.6 ppm. The ^{13}C NMR spectroscopic data was in agreement with the reported data, see ref.[6] IR (neat): $\tilde{\nu}$ = 2928, 2856, 1945, 1698, 1325, 844 cm^{-1}.

1-Phenyl-6-chlorohexa-1,2-diene (11da): Data for (*R*)-**11da**: Yield 0.142 g (68%); 98% *ee*. $[\alpha]_D^{25}$ = –152.3 (c = 0.65, $CHCl_3$). Data for (*S*)-**11da**: Yield 0.126 g (59%); 98% *ee*. $[\alpha]_D^{25}$ = +152.5 (c = 0.65, $CHCl_3$). HPLC using chiral column, chiralcel OD-H; hexanes/*i*PrOH, 100:0; flow rate 1 mL/min; 254 nm; retention times: 9.78 min (*S*) and 11.5 min (*R*). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.34–7.32 (m, 1 H), 7.23–7.20 (m, 2 H), 6.21–6.19 (d, J = 8.0 Hz, 1 H), 5.62–5.57 (d, J = 8.0 Hz, 1 H), 3.64–3.61 (t, J = 12 Hz, 2 H), 2.34–2.30 (m, 2 H), 2.0–1.96 (m, 2 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 205.2, 134.6, 128.6, 126.9, 126.6, 95.4, 93.6, 44.4, 30.2, 25.8 ppm. The ^{13}C NMR spectroscopic data was in agreement with the reported data, see ref.[6] IR (neat): $\tilde{\nu}$ = 3063, 3030, 2957, 1950, 1599, 1494, 1275, 1078, 877 cm^{-1}.

7-Phenyl-1-cyanohepta-5,6-diene (11ea): Data for (*R*)-**11ea**: Yield 0.113 g (62%); 99% *ee*. $[\alpha]_D^{25}$ = –140.2 (c = 0.60, $CHCl_3$). Data for (*S*)-**11ea**: Yield 0.107 g (58%); 97% *ee*. $[\alpha]_D^{25}$ = +135.2 (c = 0.60, $CHCl_3$). HPLC using chiral column, chiralcel OD-H; hexanes/*i*PrOH, 100:0; flow rate 1 mL/min; 254 nm; retention times: 19.6 min (*S*) and 22.1 min (*R*). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.34–7.32 (m, 1 H), 7.23–7.20 (m, 2 H), 6.23–6.20 (m, 1 H), 5.61–5.56 (d, J = 8.0 Hz, 1 H), 2.53–2.39 (m, 2 H), 2.0–1.96 (m, 2 H), 1.92–1.87 (m, 2 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 205.3, 134.3, 128.7, 127.1, 126.5, 95.8, 93.0, 27.3, 24.5, 17.5 ppm. The ^{13}C NMR spectroscopic data was in agreement with the reported data, see ref.[6] IR (neat): $\tilde{\nu}$ = 3296, 2941, 2247, 1950, 1597, 1494, 1263, 1074, 881 cm^{-1}.

1- (4-Nitrobenzyloxy)-4-phenylbuta-2,3-diene (11ga): Data for (*R*)-**11ga**: Yield 0.174 g (62%); 99% *ee*. $[\alpha]_D^{25}$ = –196.1 (c = 0.50, $CHCl_3$). Data for (*S*)-**11ga**: Yield 0.162 g (58%); 97% *ee*. $[\alpha]_D^{25}$ = +192.8 (c = 0.50, $CHCl_3$). HPLC using chiral column, chiralcel OB-H; hexanes/*i*PrOH, 85:15; flow rate 0.3 mL/min; 254 nm; retention times: 73.3 min (*R*) and 76.7 min (*S*). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 8.20–8.18 (d, J = 8.0 Hz, 2 H), 7.51–7.49 (d, J = 8.0 Hz, 2 H), 7.35–7.22 (m, 4 H), 6.31–6.29 (m, 1 H), 5.75–5.70 (m, 1 H), 4.66 (s, 2 H), 4.22–4.12 (m, 2 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 206.2, 145.8, 133.6, 128.7, 127.8, 126.9, 123.6, 95.9, 92.1, 70.6, 68.5 ppm. The ^{13}C NMR spectroscopic data was in agreement with the reported data, see ref.[6] IR (neat): $\tilde{\nu}$ = 2922, 2858, 2362, 1952, 1605, 1520, 1087, 775 cm^{-1}.

3-(Cyclohex-1-enyl)-1-phenylpropa-1,2-diene (11fa): Data for (*R*)-**11fa**: Yield 0.125 g (64%); 79% *ee*. $[\alpha]_D^{25}$ = –143.6 (c = 0.50, $CHCl_3$). Data for (*S*)-**11fa**: Yield 0.113 g (58%); 80% *ee*. $[\alpha]_D^{25}$ = +145.1 (c = 0.50, $CHCl_3$). HPLC using chiral column, chiralcel OD-H; hexanes/*i*PrOH, 99:1; flow rate 0.3 mL/min; 215 nm; retention times: 14.0 min (*S*) and 16.6 min (*R*). ^{1}H NMR (400 MHz, $CDCl_3$,): δ = 7.39–7.28 (m, 4 H), 7.23–7.18 (m, 1 H), 6.41–6.40 (d, J = 4 Hz, 1 H), 6.27–6.26 (d, J = 4 Hz, 1 H), 5.78 (s, 1 H), 2.15–2.00 (m, 4 H), 1.66–1.54 (m, 4 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 206.4, 142.0, 128.5, 128.4, 128.2, 125.8, 97.6, 91.7, 37.2, 35.5, 33.0, 32.9, 30.8, 29.7, 26.2, 26.0 ppm. The ^{13}C NMR spectroscopic data was in agreement with the reported data, see ref.[6] IR (neat): $\tilde{\nu}$ = 3028, 2924, 2858, 2858, 1930, 1599, 1493, 1074 cm^{-1}.

1-(2-Thienyl)undeca-1,2-diene (11ai): Data for (*R*)-**11ai**: Yield 0.173 g (74%); 91% *ee*. $[\alpha]_D^{25}$ = –198.3 (c = 0.45, $CHCl_3$). Data for (*S*)-**11ai**: Yield 0.164 g (71%); 99% *ee*. $[\alpha]_D^{25}$ = +215.1 (c = 0.45, $CHCl_3$). HPLC using chiral column, chiralcel OB-H; heptane/*i*PrOH, 100:0; flow rate 0.3 mL/min; 254 nm; retention times: 16.3 min (*S*) and 18.0 min (*R*). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.19–7.14 (m, 1 H), 6.96–6.88 (m, 2 H), 6.36–6.34 (m, 1 H), 5.58–5.56 (dd, 1 H), 2.37 (s, 1 H), 2.14–2.09 (m, 2 H), 1.57–1.52 (m, 2 H), 1.43–1.32 (m, 10 H), 0.94–0.92 (t, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 204.5, 139.8, 127.4, 124.1, 124.0, 95.5, 88.9, 31.8, 29.7, 29.3, 29.2, 28.8, 22.6, 21.4, 14.1 ppm. The ^{13}C NMR spectroscopic data was in agreement with the reported data, see ref.[6] IR (neat): $\tilde{\nu}$ = 3068, 2925, 2848, 1950, 1456, 1374, 1265, 1034 854 cm^{-1}.

1-(2-Thiophenyl)-6-chlorohexa-1,2-diene (11di): Data for (*R*)-**11di**: Yield 0.130 g (66%); 99% *ee*. $[\alpha]_D^{25}$ = –182.1 (c = 0.55, $CHCl_3$). Data for (*S*)-**11di**: Yield 0.126 g (64%); 99% *ee*. $[\alpha]_D^{25}$ = +184.7 (c = 0.55, $CHCl_3$). HPLC using chiral column, chiralcel OB-H; hexanes/*i*PrOH, 95:5; flow rate 0.5 mL/min; 254 nm; retention times: 13.6 min (*S*) and 14.2 min (*R*). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.17–7.15 (d, J = 8.0 Hz, 1 H), 6.96–6.90 (m, 2 H), 6.42–6.40 (m, 1 H), 5.62–5.57 (m, 1 H), 3.64–3.61 (m, 2 H), 2.36–2.24 (m, 2 H), 2.05–1.94 (m, 2 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 204.7, 139.1, 127.4, 124.6, 124.4, 94.0, 89.9, 44.3, 31.5, 25.9 ppm. The ^{13}C NMR spectroscopic data was in agreement with the reported data, see ref.[6] IR (neat): $\tilde{\nu}$ = 2955, 2926, 2854, 1950, 1738, 1442, 1261, 1039, 875 cm^{-1}.

1-(2-Furanyl)undeca-1,2-diene (11aj): Data for (*R*)-**11aj**: Yield 0.087 g (40%); 86% *ee*. $[\alpha]_D^{25}$ = –94.7 (c = 0.60, $CHCl_3$). Data for (*S*)-**11aj**: Yield 0.083 g (38%); 85% *ee*. $[\alpha]_D^{25}$ = +93.2 (c = 0.60, $CHCl_3$). HPLC using chiral column, chiralcel OD-H; hexanes/*i*PrOH, 100:0; flow rate 0.5 mL/min; 254 nm; retention times: 11.1 min (*R*) and 12.5 min (*S*). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.35 (s, 1 H), 6.38–6.37 (s, 1 H), 6.19 (s, 1 H), 6.14–6.11 (m, 1 H), 5.62–5.58 (d, 1 H), 4.64 (s, 2 H), 2.15–2.11 (m, 3 H), 1.54–1.09 (m, 13 H), 0.90–0.87 (m, 7 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 204.4, 149.0, 141.7, 111.3, 106.6, 95.7, 85.4, 31.9, 31.8, 29.4, 29.3, 29.0, 28.8, 27.1, 22.7, 14.1 ppm. The ^{13}C NMR spectroscopic data was in agreement with the reported data, see ref.[6] IR (neat): $\tilde{\nu}$ = 3115, 2926, 2824, 1952, 1585, 1464, 1344, 1079, 925 cm^{-1}.

1-(4-Nitrobenzyloxy)octan-2,3-diene (11gk): Data for (*R*)-**11gk**: Yield 0.195 g (75%); 99% *ee*. $[\alpha]_D^{25}$ = –48.8 (c = 0.60, $CHCl_3$). Data for (*S*)-**11gk**: Yield 0.176 g (68%); 98% *ee*. $[\alpha]_D^{25}$ = +48.1 (c = 0.60, $CHCl_3$). HPLC using chiral column, chiralcel AD-H; hexanes/*i*PrOH, 100:0; flow rate 1.5 mL/min; 254 nm; retention times: 29.8 min (*R*) and 34.1 min (*S*). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 8.20–8.18 (d, J = 8.0 Hz, 2 H), 7.59–7.49 (d, J = 8.0 Hz, 2 H), 5.25–5.20 (m, 2 H), 4.62 (s, 2 H), 4.09–4.07 (m, 2 H), 2.05–1.99 (m, 2 H), 1.43–1.32 (m, 4 H), 0.90–0.89 (t, J = 12.0 Hz, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 205.2, 147.3, 146.1, 127.7, 123.5, 92.2, 87.8, 70.4, 69.3, 31.2, 28.2, 22.1, 13.9 ppm. The ^{13}C NMR spectroscopic data was in agreement with the reported data, see ref.[6] IR (neat): $\tilde{\nu}$ = 2957, 2928, 2859, 2362, 2336, 1969, 1605 cm^{-1}.

5-(Cyclohexyl)-1-phenylpenta-3,4-diene (11cl): Data for (*R*)-**11cl**: Yield 0.157 g (70%); 99% *ee*. $[\alpha]_D^{25}$ = –197.3 (c = 0.70, $CHCl_3$). Data for (*S*)-**11cl**: Yield 0.153 g (68%); 97% *ee*. $[\alpha]_D^{25}$ = +194.2 (c = 0.70, $CHCl_3$). HPLC using chiral column, chiralcel OJ-H; hexanes/*i*PrOH, 100:0; flow rate 0.3 mL/min; 215 nm; retention times: 18.8 min (*S*) and 19.8 min (*R*). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.32–7.20 (m, 5 H), 5.19–5.17 (m, 1 H), 5.12–5.10 (m, 1 H), 2.76–2.72 (m, 2 H), 2.34–2.32 (m, 2 H), 1.92–1.84 (m, 1 H), 1.73–1.63 (m, 6 H), 1.38–1.26 (m, 8 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 202.8, 142.0, 128.5, 128.4, 128.2, 125.8, 97.6, 91.7, 37.2, 35.5, 33.0, 32.9, 30.8, 29.7, 26.2, 26.0 ppm. The ^{13}C NMR spectroscopic data was in agreement with the reported data, see ref.[6] IR (neat): $\tilde{\nu}$ = 3026, 2924, 2851, 1959, 1728, 1450, 1057 cm^{-1}.

1,3-Diphenylpropan-1,2-diene (11ba): Data for (*R*)-**11ba**: Yield 0.081 g (42%); 79% *ee.* $[\alpha]_D^{25}$ = –723.1 (*c* = 0.65, $CHCl_3$). Data for (*S*)-**11ba**: Yield 0.073 g (38%); 79% *ee.* $[\alpha]_D^{25}$ = +726.7 (*c* = 0.65, $CHCl_3$). HPLC using chiral column, chiralcel OD-H; hexanes/*i*PrOH, 99:1; flow rate 0.5 mL/min; 254 nm; retention times: 11.0 min (*R*) and 14.4 min (*S*). ^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.36–7.30 (m, 8 H), 7.25–7.21 (m, 2 H), 6.60 (s, 2 H) ppm. ^{13}C NMR (125 MHz, $CDCl_3$): δ = 207.8, 133.6, 128.7, 127.3, 127.0, 98.4 ppm. The ^{13}C NMR spectroscopic data was in agreement with the reported data, see ref.[6] IR (KBr): $\tilde{\nu}$ = 3061, 3028, 1936, 1597, 1493, 1450, 758 cm^{-1}.

3-Cyclohexyl-1-phenyl-1,2-propadiene (11bl): Data for (*R*)-**11ba**: Yield 0.134 g (68%); 83% *ee.* $[\alpha]_D^{25}$ = –135.1 (*c* = 0.70, $CHCl_3$). Data for (*S*)-**11ba**: Yield 0.122 g (62%); 91% *ee.* $[\alpha]_D^{25}$ = +152.1 (*c* = 0.70, $CHCl_3$). HPLC using chiral column, chiralcel OD-H; heptane/*i*PrOH, 100:0; flow rate 1 mL/min; 214 nm; retention times: 5.4 min (*R*), and 7.2 min (*S*). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.31–7.24 (m, 4 H), 7.23–7.17 (m, 1 H), 6.21–6.11 (m, 1 H), 5.62–5.52 (m, 1 H), 2.22–2.04 (m, 1 H), 1.93–1.57 (m, 5 H), 1.41–1.09 (m, 5 H) ppm. ^{13}C NMR (125 MHz, $CDCl_3$): δ = 204.0, 135.2, 128.5, 126.6, 126.4, 101.0, 95.4, 37.6, 33.2, 33.1, 26.1, 26.0 ppm. The ^{13}C NMR spectroscopic data was in agreement with the reported data, see ref.[6] IR (KBr): $\tilde{\nu}$ = 3061, 3028, 1936, 1597, 1493, 1450, 758 cm^{-1}.

Supporting Information (see footnote on the first page of this article): Chiral HPLC analysis data and ^{1}H and ^{13}C NMR spectra for all new compounds.

Acknowledgments

The authors are thankful to the Department of Science and Technology (DST) for support of a J. C. Bose National Fellowship grant to M. P., and for the FIST and IRPHA programs. The support of the University Grants Commission (UGC) under the UPE and CAS programs is also gratefully acknowledged. N. S. K. and P. O. R are grateful to the Council of Scientific and Industrial Research (CSIR), New Delhi for research fellowships.

[1] a) A. Hoffmann-Röder, N. Krause, *Angew. Chem.* **2004**, *116*, 1216; *Angew. Chem. Int. Ed.* **2004**, *43*, 1196; b) M. Brasholz, H. U. Reissig, R. Zimmer, *Acc. Chem. Res.* **2009**, *42*, 45; c) B. Alcaide, P. Almendros, T. M. del Campo, *Chem. Eur. J.* **2010**, *16*, 5836; d) N. Krause, C. Winter, *Chem. Rev.* **2011**, *111*, 1994; e) F. Inagaki, S. Kitagaki, C. Mukai, *Synlett* **2011**, 594; f) F. Lopez, J. L. Mascarenas, *Chem. Eur. J.* **2011**, *17*, 418; g) S. Yu, S. Ma, *Angew. Chem.* **2012**, *124*, 3128; *Angew. Chem. Int. Ed.* **2012**, *51*, 3074.

[2] a) . A. G. Myers, B. Zheng, *J. Am. Chem. Soc.* **1996**, *118*, 4492; b) Z. Wan, S. G. Nelson, *J. Am. Chem. Soc.* **2000**, *122*, 10470; c) C.-Y. Li, X.-L. Sun, Q. Jing, Y. Tang, *Chem. Commun.* **2006**, 2980; d) X. Pu, J. M. Ready, *J. Am. Chem. Soc.* **2008**, *130*, 10874; e) . H. Liu, D. Leow, K.-W. Huang, C.-H. Tan, *J. Am. Chem. Soc.* **2009**, *131*, 7212; f) . E. M. Woerly, A. H. Cherney, E. K. Davis, M. D. Burke, *J. Am. Chem. Soc.* **2010**, *132*, 6941.

[3] a) N. Krause, A. S. K. Hashmi (Eds.), *Modern Allene Chemistry*, Wiley-VCH, Weinheim, Germany, **2004**; b) A. S. K. Hashmi, *Angew. Chem.* **2000**, *112*, 3737; *Angew. Chem. Int. Ed.* **2000**, *39*, 3590; c) R. W. Bates, V. Satcharoen, *Chem. Soc. Rev.* **2002**, *31*, 12; d) N. Krause, A. Hoffmann-Röder, *Tetrahedron* **2004**, *49*, 11671; e) S. Ma, *Chem. Rev.* **2005**, *105*, 2829; f) K. M. Brummond, J. E. DeForrest, *Synthesis* **2007**, 795; g) M. Ogasawara, *Tetrahedron: Asymmetry* **2009**, *20*, 259; h) M. A. Schade, S. Yamada, P. Knochel, *Chem. Eur. J.* **2011**, *17*, 4232.

[4] a) V. K.-Y. Lo, M.-K. Wong, C.-M. Che, *Org. Lett.* **2008**, *10*, 517; b) V. K.-Y. Lo, V. C.-Y. Zhou, M.-K. Wong, C.-M. Che, *Chem. Commun.* **2010**, *46*, 213; c) J. Ye, S. Li, B. Chen, W. Fan, J. Kuang, J. Liu, Y. Liu, B. Miao, B. Wan, Y. Wang, X. Xie, Q. Yu, W. Yuan, S. Ma, *Org. Lett.* **2012**, *14*, 1346.

[5] a) P. Crabbe, H. Fillion, D. Andre, J.-L. Luche, *J. Chem. Soc., Chem. Commun.* **1979**, 859; b) J. Kuang, S. Ma, *J. Am. Chem. Soc.* **2010**, *132*, 1786.

[6] M. Periasamy, N. Sanjeevakumar, M. Dalai, R. Gurubrahamam, P. O. Reddy, *Org. Lett.* **2012**, *14*, 2932.

[7] M. Periasamy, N. Sanjeevakumar, P. O. Reddy, *Synthesis* **2012**, *44*, 3185.

[8] G. Lowe, *J. Chem. Soc., Chem. Commun.* **1965**, 411.

[9] a) C. S. Tomooka, R. Fassler, D. E. Frantz, E. M. Carreira, *Proc. Natl. Acad. Sci. USA* **2004**, *101*, 5843; b) C. Fischer, E. M. Carreira, *Org. Lett.* **2004**, *6*, 1497.

[10] X-ray crystallography: CCDC-914858 (for **15**) and CCDC-914859 (for **18**) contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

Received: February 13, 2013
Published Online: May 5, 2013

