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Diastereoselective Synthesis of Tetrasubstituted Propargylamines via Hydroamination and Metalation of 1-Alkynes and Their Enantioselective Conversion to Trisubstituted Chiral Allenes

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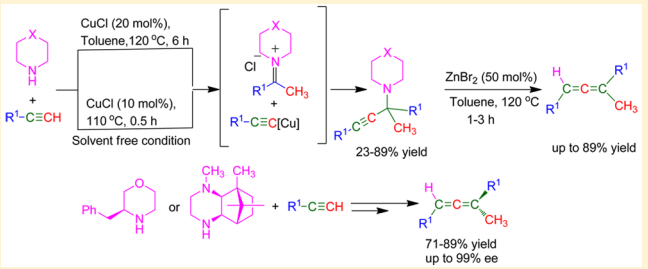
Supporting Information

ABSTRACT: Reaction of cyclic secondary amines with 1-alkynes and copper(I) chloride at 110−120 °C gives the corresponding alkynylcopper complex, which adds to the iminium ion intermediate formed in situ by hydroamination of 1-alkynes to give the corresponding propargylamine derivatives in up to 94% yield and 99% regioselectivity. The diastereomerically pure chiral propargylamines were obtained in 23−89% yield using optically active 2-benzyl morpholine and *N*-methyl camphanyl piperazine. These chiral propargylamines are readily converted to the corresponding trisubstitued chiral allenes in 71−89% yields with up to 99% ee upon reaction with $ZnBr_2$ at 120 °C. The results are discussed considering mechanisms involving diastereoselective addition of alkynylcopper complex formed in situ to iminium ions formed in situ regioselectively to produce the corresponding propargylamines, which in turn give the chiral allenes with very high enantioselectivity via an intramolecular 1,5-hydrogen shift in the presence of zinc bromide.



INTRODUCTION

In recent years, there have been several reports on the hydroamination of alkynes.[1] For example, it has been reported that $Zn(OTf)_2$ promotes hydroamination of 1-alkynes using amines to give ketimine or keteminium intermediates, which upon reduction, give trisubstituted amines.[2] Metal salts like ZnX_2 and CuX also promote metalation of 1-alkynes to produce alkynyl metal intermediates, which could add to the keteiminium intermediates.[3] Accordingly, we have envisaged the generation of iminium ions and alkynylmetal intermediates[4] in situ for the synthesis of chiral propargylamines, which in turn could be converted to trisubstituted chiral allenes. Herein, we describe the results of detailed studies on the synthesis of tetrasubstituted chiral propargylamines and trisubstituted chiral allenes from 1-alkynes (Scheme 1).

RESULTS AND DISCUSSION

Initially, we carried out experiments using 1-decyne and morpholine for the reaction with $ZnCl_2$ or $ZnBr_2$ at 120 °C. Propargylamine **7aa** was not formed under these conditions (entries **1** and **2**, Table 1), but it was formed in 15% yield in 24 h (entry **3**, Table 1) when ZnI_2 was used and in 27% yield when $Zn(OTf)_2$ was used (entry **4**, Table 1)

Interestingly, when the reaction was carried out using $Zn(OTf)_2$ without using toluene at 120 °C, propargylamine **7aa** was formed in 69% yield within 2 h (entry **5**, Table 1). Further screening led to the observation that the cheaper CuCl plays the same role, affording **7aa** in 83% yield (entry **8**, Table 1). Propargylamine **7aa** was also obtained in similar yields using other copper halides like CuBr and CuI under this reaction condition along with allene byproduct (entry **11**, Table 1). The reaction temperature was also found to be crucial for this transformation. Elevating the temperature above 110 °C led to formation of more amounts of the trisubstituted allene **8a** (entry **9**, Table 1), whereas lowering the temperature to 100 °C resulted in lower yields of the propargylamine product **7aa** (entry **12**, Table 1). However, experiments carried out at different temperatures and time interval conditions to obtain the trisubstituted allene **8a** as major product in a single-pot operation were not successful. The copper(II) salts CuX_2 (Cl or Br) are not effective, but $Cu(OTf)_2$ affords product **7aa** in 92% yield within 0.5 h at 100 °C (entry **12** and **13**, Table 1). Although the use $Cu(OTf)_2$ gave better results, we have explored the scope of the reaction using CuCl (Table 1, entries **6** and **8**) as it is less expensive. The results are summarized in Table 2.

The reaction of morpholine and other 1-alkynes like 1-octyne **2b** and 1-heptyne **2c** gave the corresponding tetrasubstituted propargylamines **7ab** and **7ac** in 73−79% yields. The 1-alkynes, such as 3-cyclohexyl-1-propyne (**2d**), 2-cyclohexyl-1-acetylene (**2e**), and 4-phenyl-1-butyne (**2g**), furnished the corresponding products in up to 85% yield. The functionalized alkynes like 6-cyano-1-hexyne (**2j**), 1-

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Scheme 1. Synthesis of Tetrasubstituted Chiral Propargylamines and Trisubstituted Chiral Allenes

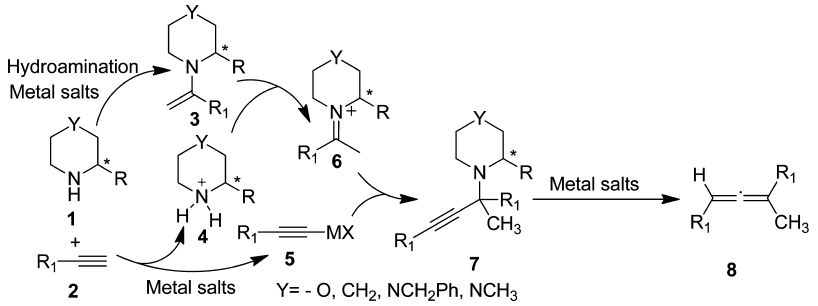
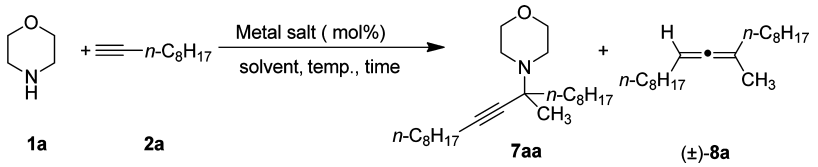


Table 1. Reaction of Morpholine 1a and 1-Decyne 2a with Different Metal Salts to Produce Tetrasubstituted Propargylamine 7aa[a]



1a 2a 7aa (±)-8a

s. no	solvent	temp. (°C)	MX_n	mol (%)	time (h)	7aa yield (%)
1	toluene	120	$ZnCl_2$	5	24	
2	toluene	120	$ZnBr_2$	5	24	
3	toluene	120	ZnI_2	5	24	15
4	toluene	120	$Zn(OTf)_2$	5	24	27
5		120	$Zn(OTf)_2$	5	2	69
6	toluene	120	CuCl	20	6	80
7		110	CuCl	5	0.5	68
8		110	CuCl	10	0.5	83
9[b]		120	CuCl	10	0.5	71
10[b]		110	CuBr	10	0.5	79
11[b]		110	CuI	10	0.5	77
12		100	CuCl	10	0.5	69
13		100	$Cu(OTf)_2$	5	0.5	92

[a]The reactions were carried out using morpholine **1a** (1.0 mmol) and 1-decyne **2a** (2.2 mmol). [b]Allene **8a** was formed in 7−12% yields as determined by ^{1}H NMR spectral analysis of the crude reaction mixture.

methoxy-10-decyne (**2k**), and 1-*tert*-butyldimethylsilyloxy-5-hexyne (**2l**) afforded the corresponding propargylamines in 74−81% (**7aj**), 69−73% (**7ak**), and 62−69% (**7al**) yields, respectively.

When the reaction was carried out with phenylacetylene **2f** and morpholine **1a** in solvent-free conditions at 110 °C, tetrasubstituted propargylamine **7af** was obtained in 29% along with some unidentified products, but the reaction in toluene solvent resulted in only a mixture of unidentified products being formed, and amine **7af** was not obtained. We have also observed that the reaction of 1-decyne **2a** with different cyclic amine derivatives (**1b−1f**) led to the corresponding tetrasubstituted propargylamines **7ba−7fa** in 72−83% yields.

It was of interest to us to examine whether the hydroamination reaction under these conditions would give the corresponding chiral propargylamines with diastereoselectivity if enantiomerically pure chiral amines are used. Accordingly, we have examined the use of different readily accessible optically active chiral secondary amines **1g−1l** (Figure 1).[5]

The chiral amines **1g**, **1h**, and **1k** failed to give the corresponding propargylamines under these conditions, presumably due to the sterically crowded nature of these amines. The relatively less hindered chiral amine **1i** did give the corresponding tetrasubstituted propargylamine **7ia** in 45% yield along with the trisubstituted propargylamine **9ia** in 37% yield in the reaction using CuCl in toluene at 120 °C (Scheme 2). When the reaction was carried out without using toluene, better selectivity was realized as the tetrasubstituted propargylamine **7ia** was obtained in 79% yield along with the trisubstituted propargylamine **9ia** (11% yield) (Scheme 2, eq-1). The reaction using the chiral morpholine derivative **1j** in toluene gave the diastereomerically pure tetrasubstituted propargylamine **7ja** in 76% yield, and the other diastereomer was not obtained (Scheme 2, eq-2). Slightly higher yield (87%) was realized in the experiment without using toluene. Whereas the optically active *N*-methyl camphanyl piperazine **1l** gave an unidentified mixture of products in toluene, the diastereomerically pure chiral propargylamine **7la** was obtained in 68% yield under solvent-free conditions. The presence of the other diastereomers in the product could not be detected by ^{1}H and ^{13}C NMR spectral analysis, but in this experiment, ketone **10a** was obtained as a side product in 14% yield (Scheme 2, eq-3).

We have carried out several experiments using the chiral morpholine **1j** with different alkynes, and the results are summarized in Table 3. The reactions using 1-alkyne **2b** and **2c** gave the corresponding propargylamines in 64−86% yield. The reaction is also applicable to substituted aliphatic 1-alkynes as illustrated by reactions using the alkynes **2d**, **2e**, **2g**, **2h**, and **2i**.

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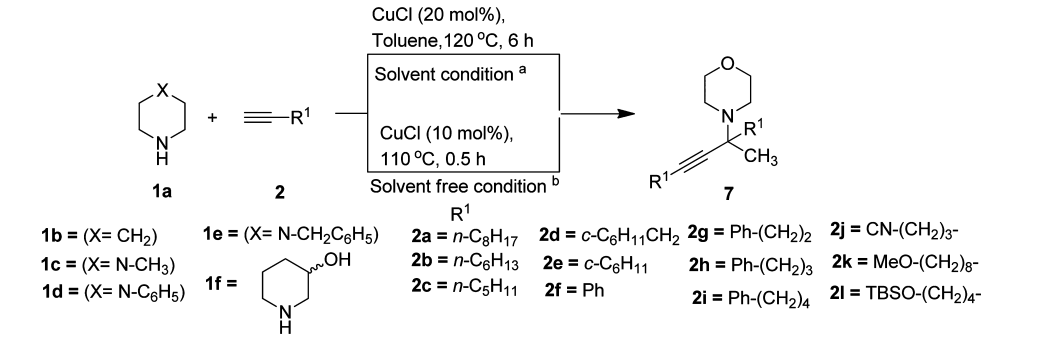
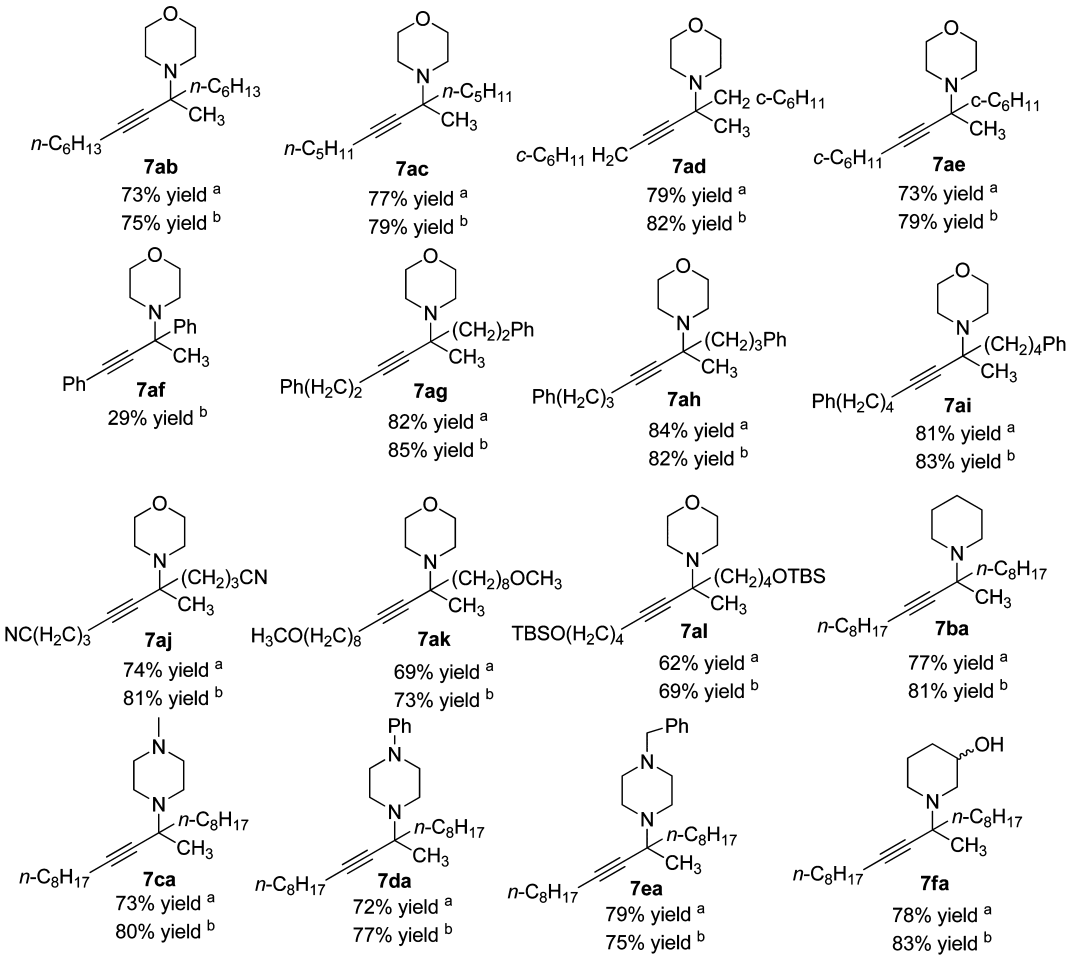
Table 2. Synthesis of Propargylamine 7 Using Cyclic Amines 1 and 1-Alkyne 2





[a]The reactions were carried out by using amine (1.0 mmol) and 1-alkyne (2.2 mmol) in toluene (3 mL) at 120 °C for 6 h. [b]The reactions were carried out by using amine (1.0 mmol) and 1-alkyne (2.2 mmol) at 110 °C for 0.5 h.

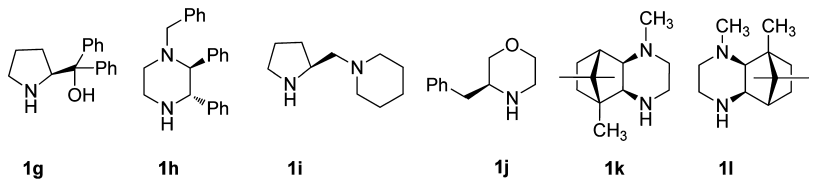


Figure 1. Chiral amines (**1g**−**1l**) used in CuCl-catalyzed chiral propargylamine synthesis.

The corresponding propargylamines were obtained in 59−83% yields in these experiments. Similarly, the 1-alkynes **2j**, **2k**, and **2l** also gave the corresponding diastereomerically pure propargylamines with reasonable to good yields.

The configurations at the newly formed stereogenic centers were assigned as (*S*) on the basis of X-ray single crystal structure analysis of propargylamine **7jf** (Figure S2).

We have observed that the chiral propargylamines **7ja**−**7jk** react with $ZnBr_2$ at 120 °C to give the corresponding allenes

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Scheme 2. Synthesis of Chiral Propargylamines from 1-Alkynes Using Chiral Amines (1i−1l)

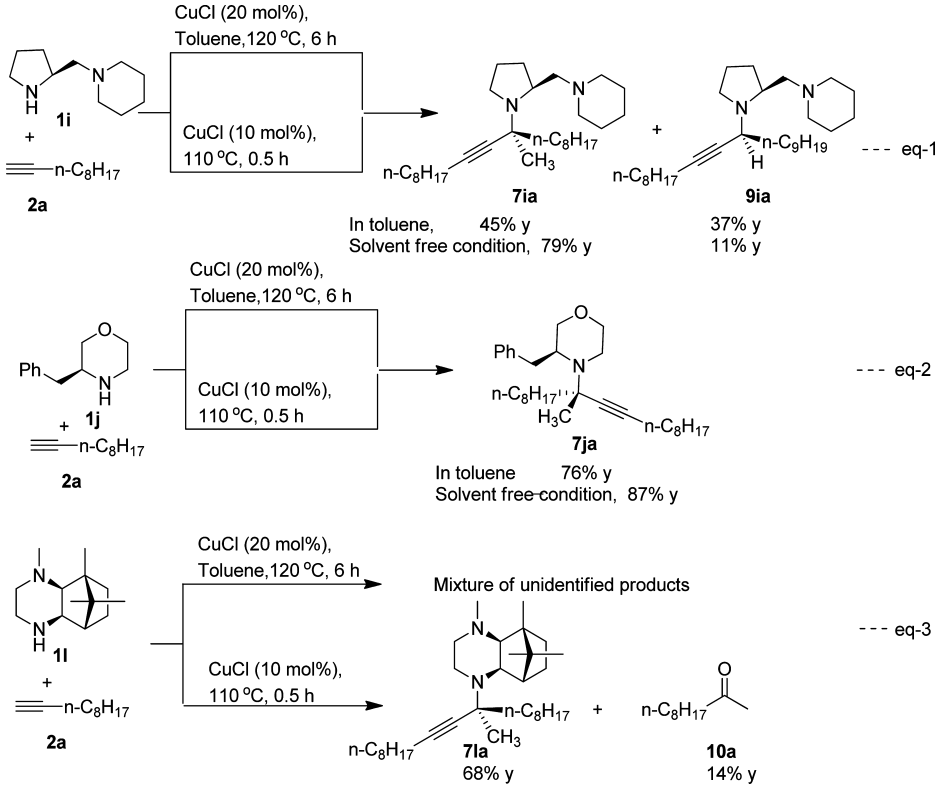
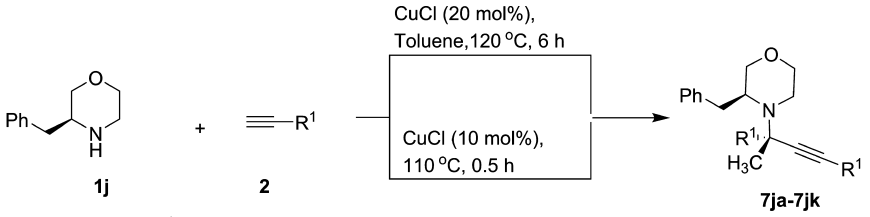


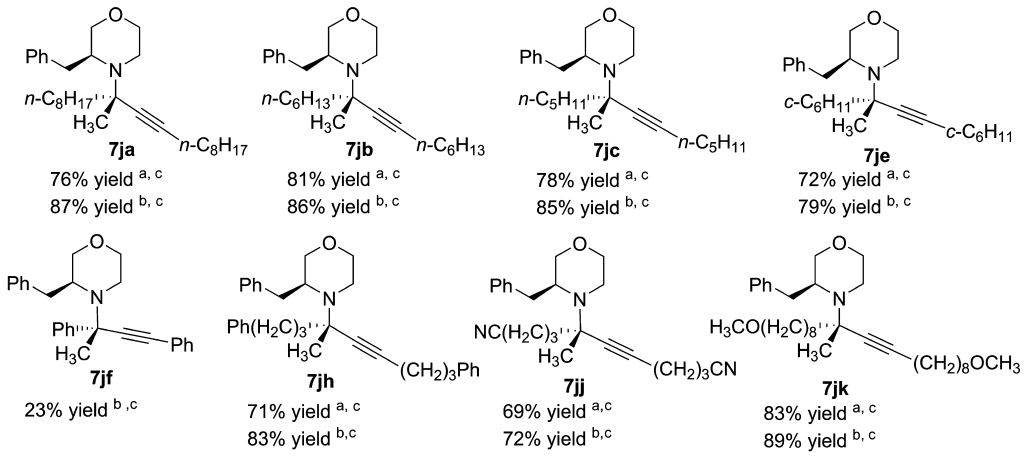
Table 3. Synthesis of Chiral Propargylamine 7 Using 1-Alkyne 2 and the Chiral Amine 1j Using CuCl



R^1

2a = *n*-C_8H_{17} **2c** = *n*-C_5H_{11} **2f** = Ph **2j** = CN-$(CH_2)_3$-

2b = *n*-C_6H_{13} **2e** = *c*-C_6H_{11} **2h** = Ph-$(CH_2)_3$- **2k** = MeO-$(CH_2)_8$-



[a]The reactions were carried out using amines (1.0 mmol) and 1-alkyne (2.2 mmol) in toluene (3 mL) at 120 °C for 6 h. [b]The reactions were carried out using amines (1.0 mmol) and 1-alkyne (2.2 mmol) at 110 °C for 0.5 h. [c]In all reactions, the propargylamine derivatives 7 were obtained in diastereomerically pure form, and the other diastereomer could not be detected by ^{1}H NMR or ^{13}C NMR spectral data.

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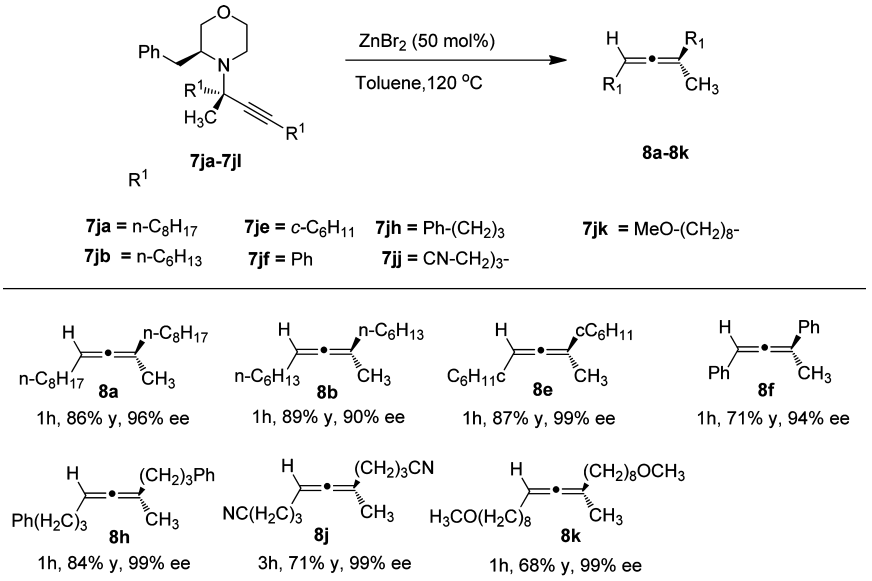
Table 4. $ZnBr_2$-Promoted Conversion of Chiral Propargylamines to Chiral Allenes[a]



[a]The reactions were carried out using propargylamine (1 mmol), which was obtained from chiral morpholine **1j** in toluene (3 mL) with $ZnBr_2$ (0.5 mmol) at 120 °C. Yield of allenes. The ee was determined by chiral HPLC analysis.

8a–**8k** in 68–89% yields (Table 4). The propargylamines having functionalized groups also afforded the chiral allenes **8j** and **8k** in 68–71% yields with up to 99% ee. All propargylamines are converted to the corresponding chiral allenes **8** within 1–3 h under these reaction conditions (Table 4). All of the optically active allenes obtained using chiral amines **1j** are levorotatory. Hence, the absolute configurations of the major enantiomer of the chiral allenes are assigned as *R* based on the Lowe–Brewster rule[6a,b] and the Taft[6c] and Runge[6d,e] polarizabilty parameters expected for the substituents in these allenes.[6f]

In recent years, several enantiomerically enriched chiral trisubstituted allenes were reported, but their configurations were assigned based only on reaction mechanisms without even considering the Lowe–Brewster rule. Hence, it is desirable to briefly discuss the assignment of configuration for the enantiomerically enriched trisubstituted allenes considering the Lowe–Brewster rule. The chiral allenes may be considered to have the structures with substituents **A** and **B** at one allene end and groups **X** and **Y** at the other allene end, as depicted in Figure 2. In the Lowe model,[6a] the group with highest polarity **A** is placed at the top [Figure 2, structure (a)] and the other group **B** is also placed above the plane with the **X** and **Y** groups placed in the sides below the plane. The Lowe rule predicts the allene to be levorotatory with $(-)[\alpha]_D$ if the polarizability of the group **X** > **Y** and the allene to be dextrorotatory with $(+)[\alpha]_D$ if the polarizability is **Y** > **X**. For disubstitued chiral allenes, the Cahn–Ingold–Prelog (CIP) priority rules will be in the order **A** > **B** (**B**=H), **X** > **Y** (**Y**=H). Hence, the disubstitued allene with (*R*) configuration will have $(-)[\alpha]_D$, and the corresponding enantiomer will have $(+)[\alpha]_D$ value with (*S*) configuration. This will also be the case for enantiomerically enriched trisubstituted allenes **8a**–**8k** [**A** (**A**=Ph or alkyl) > **B** (**B**=CH_3), **X** (X= Ph or alkyl) > **Y** (**Y**=H) reported here, where the expected Lowe–Brewster polarizability order and the CIP priority order are the same as in disubstituted allenes. Hence, the enantiomerically enriched trisubstituted allene derivatives **8a**–**8k** with $(-)[\alpha]_D$ values are assigned to the

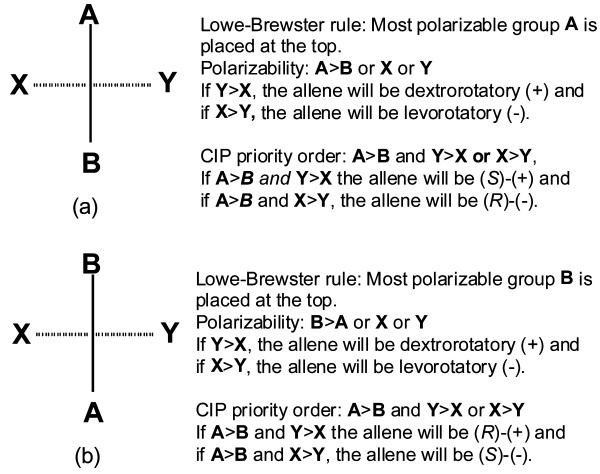


Figure 2. Configuration of allenes and sign of $[\alpha]_D$ values based on Brewster–Lowe–Taft–Runge polarizability order and Cahn–Ingold–Prelog (CIP) priority rules.

(*R*) configuration. Therefore, the (*R*)-(+) configuration reported for the enantiomerically enriched chiral allene with same substituents as in **8f** (Ph, CH_3 and Ph, H) but with $[\alpha]_D$ +122.4 should be corrected as (*S*)-(+).[6h] Presumably, the (*R*)-(+) configuration was assigned erroneously in the earlier report[6h] by comparison with incorrect drawing of the allene structure (substituents Ph, *n*-Bu and Ph, H) with $[\alpha]_D$ +251 for which the original authors did not assign the configuration.[6g]

An interesting possibility is that a group may have higher priority as per the CIP rules but may not have the highest polarizability [Figure 2, structure (b)]. In such cases, the allene with (*R*) configuration will give $(+)[\alpha]_D$ and its (*S*) enantiomer will give $(-)[\alpha]_D$ values as per the Lowe–Brewster rule. There are several reports assigning (*R*)-(+) and (*S*)-(−) configurations for trisubstituted allenes based on reaction mechanisms,[7a–d] but in these reports, the Lowe–Brewster and Taft–Runge polarizability and the CIP priority order for the substituents were not considered while assigning configura-

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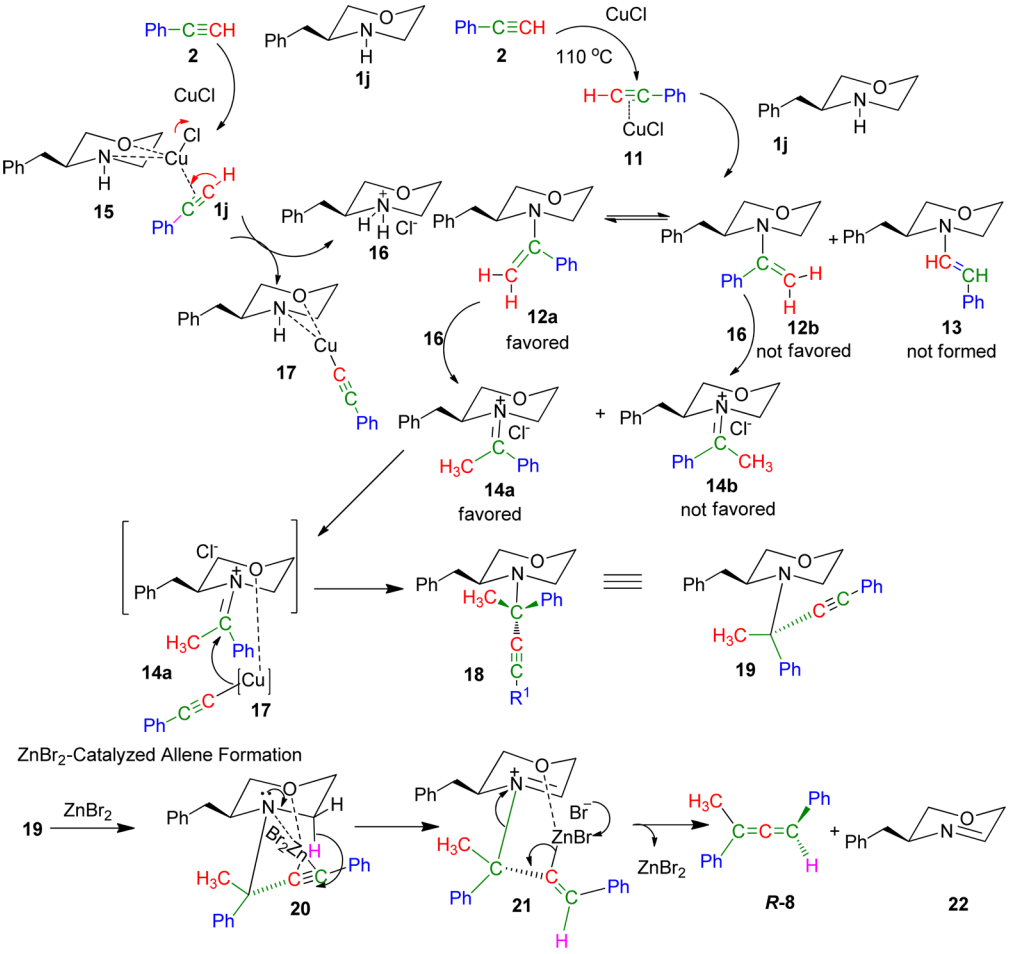
Scheme 3. Tentative Mechanism for the Formation of Chiral Propargylamines Using Chiral Amine 7j and Their Conversion to Chiral Allenes



tions, and the assigned configurations were also not confirmed by X-ray structure analysis or NMR spectral analysis with chiral solvating agents as was done in some other cases.[7e,f] Such ambiguity is also expected in assigning configurations for tetrasubstituted chiral allenes.[7g] Needless to say, because the Lowe−Brewster rule is based on the sign of optical rotation, this method of assigning configuration may not be reliable if the magnitude of the $[\alpha]_D$ value is small. In this regard, it may be of interest to note that an interesting spontaneous resolution of tetrasubstituted allenic phosphinate derivatives was reported recently, and the enantiomers were characterized by X-ray structure analysis but the samples did not have significant $[\alpha]_D$.[7h] Presumably, the differences in polarizability of substituents are small in these cases.

The CuCl-catalyzed formation of propargylamines **7la−7ll** and their conversion to chiral allenes by $ZnBr_2$-promoted transformation can be explained by the tentative mechanism and intermediates outlined in Scheme 3. Initially, chiral amine **1** would react with CuCl to form complex **15**.[8] Then, its reaction with 1-alkyne would give intermediate complex **17**, which could react with the intermediate **14a** formed in situ via hydroamination of alkyne through the intermediates **11**, **12a**, and **16** (Scheme 3).[4] Delivery of the alkynyl group from the bottom face of the ketiminium ion species would lead to the new (*S*)-stereogenic center at propargylamine product **19** (Figure S1) that could complex with $ZnBr_2$ to give intermediate **20**, which after an intramolecular hydride shift and addition of H and ZnBr group across the triple bond would give intermediate **21** that after elimination of $ZnBr_2$ and imine **22** would afford chiral allene (*R*)-**8** (Scheme 3).[5,9] An important aspect of this tentative mechanism for the $ZnBr_2$-promoted conversion of propargylamine **19** to allene (*R*)-**8** is the interaction of the morpholine oxygen with the $ZnBr_2$ moiety during the transformation (Scheme 3). Although there is no direct evidence for this mechanism, previously only poor selectivity was realized in the chiral disubstituted allene synthesis from enantiomerically pure propargylamines obtained using 1-alkyne, benzaldehyde, and simple chiral 2-phenyl pyrrolidine system where there is no additional oxygen or nitrogen coordination site available.[5a]

Enantiomerically pure chiral camphanyl propargylamine derivatives of **7l** are also readily prepared in 68−89% yields from the corresponding camphanyl amine **1l** under solvent-free conditions (Table 5).

Unfortunately, these propargylamine derivatives **7la−7ll** failed to crystallize, but the configurations of the newly formed stereocenters were assigned as (*S*) based on their conversion to the chiral (*R*) allenes as the mechanism of formation of enantiomerically enriched trisubstituted chiral allenes (Scheme 4) is expected to be same as the mechanism for conversion of tetrasubstituted morpholinyl propargylamine derivatives (Scheme 3). The chiral propargylamines **7la−7ll** react with $ZnBr_2$ at 120 °C to give the corresponding allenes **8a−8l** in 68−90% yield at 120 °C (Table 6). The propargylamines

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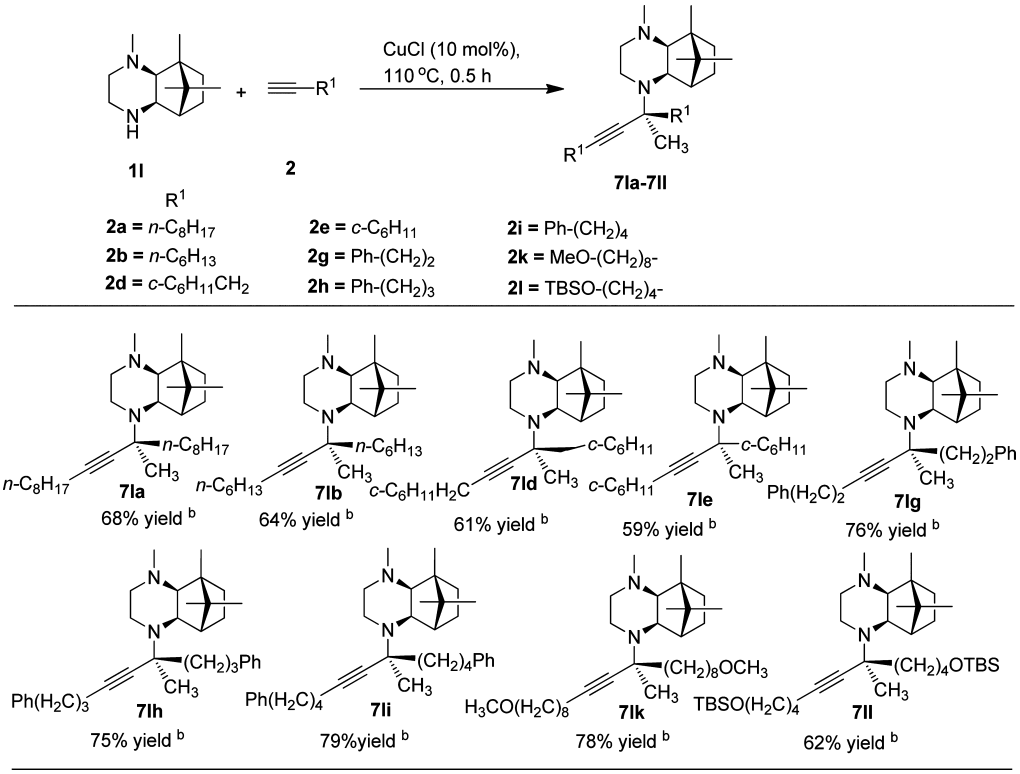
Table 5. Synthesis of Chiral Propargylamine 7 Using 1-Alkyne 2 and the Chiral Amine 1l Using CuCl[a]



[a]The reactions were carried out using amines (1.0 mmol) and 1-alkyne (2.2 mmol) at 110 °C for 0.5 h. In all reactions, the propargylamine derivatives 7 were obtained in diastereomerically pure forms, and the other diastereomer could not be detected by ^{1}H NMR or ^{13}C NMR spectral data. [b]Yield of propargylamines.

having functionalized groups also afforded the chiral allenes **8a**–**8l** and in 68–90% yields with up to 99% ee. It was also found that all propargylamines are converted to the corresponding chiral allenes **8** within 1–3 h under these reaction conditions (Table 6). All the optically active allenes obtained using chiral amines **1l** are levorotatory from which the absolute configurations of the major enantiomers of the chiral allenes are assigned as *R* by the Lowe–Brewster rule considering the Taft–Runge polarizability order expected for the substituents in these allene derivatives (Figure 2).[6]

We have also found that the imine byproducts **22** and **34** could be easily reduced before workup to the starting chiral secondary amines **1j** or **1l** in 62–72% yields by adding sodium borohydride in methanol at −20 °C and bringing the contents to 25 °C and stirring for 2 h.

CONCLUSIONS

We have developed a convenient method for the synthesis of tetrasubstituted propargylamine derivatives via the CuCl-catalyzed hydroamination of 1-alkynes using the achiral amine derivatives. In addition, we have devised a method for the diastereoselective synthesis of chiral propargylamine derivatives using chiral amines. Furthermore, we have converted these chiral propargylamine derivatives to trisubstituted chiral allenes in high enantiomeric purities using zinc bromide. Therefore, the methods described herein have considerable potential for further synthetic applications.

EXPERIMENTAL SECTION

General Procedure for the Synthesis of Tetrasubstituted Propargylamines 7 from 1-Alkyne and Amines 1 with CuCl in Solvent Conditions. To a stirred suspension of amines **1** (1 mmol) were added CuCl (0.020 g, 0.2 mmol) and 1-alkyne **2** (2.2 mmol) in toluene (3 mL) at 25 °C under N_2 atmosphere. The contents were stirred at 120 °C for 6 h. The reaction mixture was cooled to room temperature. Toluene was removed using reduced pressure. Water (5 mL) and DCM (15 mL) were added. The DCM layer was washed with saturated NaCl solution, dried (Na_2SO_4), and concentrated. The residue was subjected to column chromatography using hexane and ethyl acetate (90:10) as eluent to isolate propargyl amines **7**.

General Procedure for the Synthesis of Tetrasubstituted Propargylamines 7 from 1-Alkyne and Amine 1 with CuCl in Solvent-Free Conditions. To a stirred suspension of amines **1** (1 mmol) were added CuCl (0.010 g, 0.1 mmol) and 1-alkyne **2** (2.2 mmol) in sealed tube at 25 °C under N_2 atmosphere. The contents were stirred at 110 °C for 0.5 h. The reaction mixture was cooled to room temperature. Water (5 mL) and DCM (15 mL) were added. The DCM layer was washed with saturated NaCl solution, dried (Na_2SO_4), and concentrated. The residue was subjected to column chromatography using hexane and ethyl acetate (90:10) as eluent to isolate propargylamines **7**.

*4-(9-Methylnonadec-10-yn-9-yl)morpholine (**7aa**).* Using toluene as solvent (Table 2): 0.290 g, 80% yield. Under solvent-free conditions (Table 2): 0.301 g, 83% yield. Colorless oil; R_f = 0.6 (silica gel, 90:10 hexane/EtOAc); IR (neat) 3029, 2947, 2854, 1599, 1495, 1451, 1391, 1352, 1128 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.70 (t, J = 4.0 Hz, 4H), 2.59–2.57 (m, 4H), 2.17 (t, J = 8.0 Hz, 2H), 1.48–1.39 (m, 4H), 1.38–1.23 (m, 25H), 0.87 (t, J = 8.0 Hz, 6H); ^{13}C{1H} NMR (100 MHz, $CDCl_3$) δ 84.5, 81.6, 67.4, 57.5, 47.0, 39.3, 31.8, 30.0, 29.5, 29.3, 29.2, 29.1, 29.0, 28.8, 24.0, 23.7, 22.6, 18.6, 14.0; LCMS m/z 364 [M + 1]; anal. calcd for $C_{24}H_{45}NO$ C 79.27, H 12.47, N 3.85; found C 79.35, H 12.41, N 3.91.

*4-(7-Methylpentadec-8-yn-7-yl)morpholine (**7ab**).* Using toluene as solvent (Table 2): 0.224 g, 73% yield. Under solvent-free conditions (Table 2): 0.230 g, 75% yield. Colorless oil; R_f = 0.6 (silica gel, 90:10 hexane/EtOAc); IR (neat) 2953, 2916, 2845, 2820, 1435, 1118, 945,

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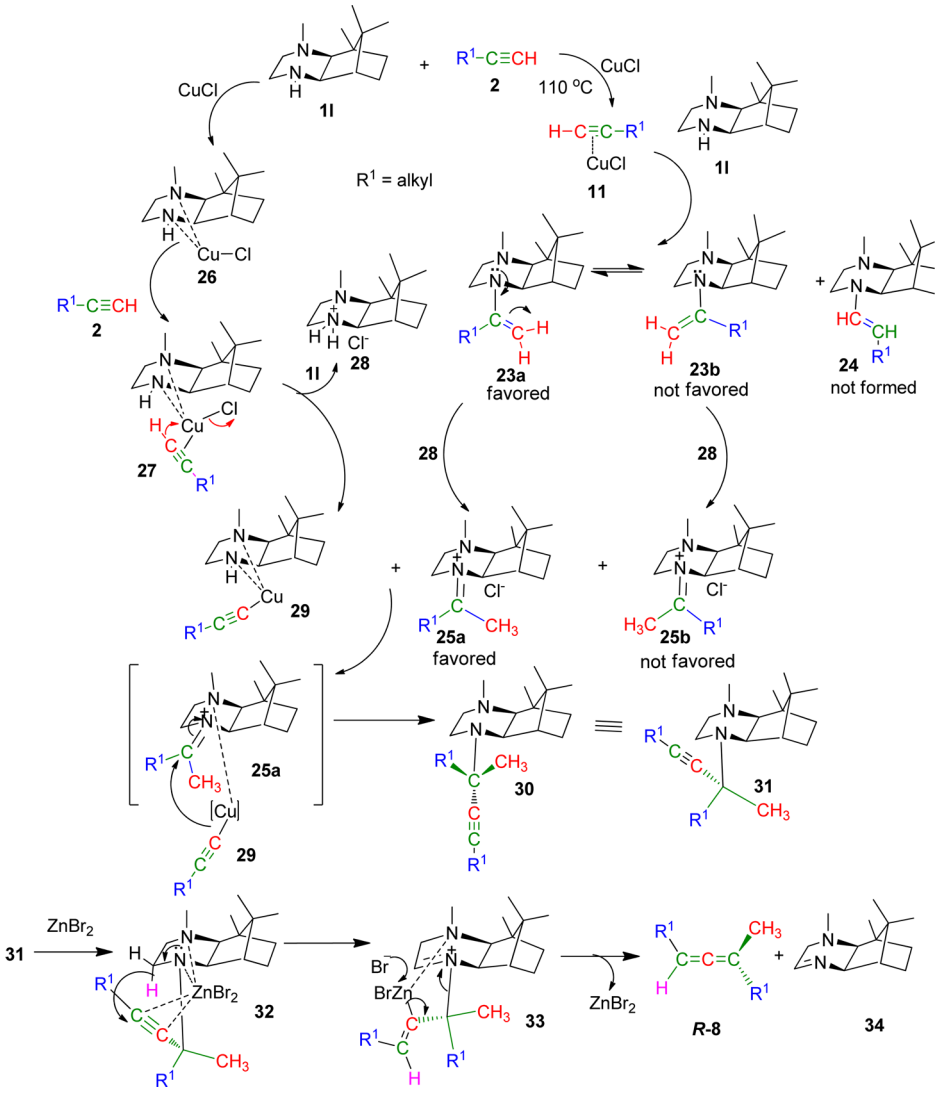
Scheme 4. Tentative Mechanism for the Formation of Chiral Propargylamines Using Chiral Amines 7l and Their Conversion to Chiral Allenes



cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.02 (t, J = 8.0 Hz, 4H), 2.48 (t, J = 8.0 Hz, 2H), 2.22−2.15 (m, 4H), 1.66−1.55 (m, 6H), 1.39 (s, 3H), 1.26−1.17 (m, 5H), 1.09−0.98 (m, 3H), 0.90−0.88 (m, 7H), 0.79−0.77 (m, 3H); ^{13}C{1H} NMR (100 MHz, $CDCl_3$) δ 84.4, 81.5, 67.4, 57.4, 47.0, 39.3, 31.8, 31.3, 29.0, 28.5, 23.9, 23.7, 22.6, 22.5, 18.5, 14.0; LCMS m/z 307 [M + 1]; anal. calcd for $C_{20}H_{37}NO$ C 78.11, H 12.13, N 4.55; found C 78.23, H 12.06, N 4.48.

*4-(6-Methyltridec-7-yn-6-yl)morpholine (**7ac**).* Using toluene as solvent (Table 2): 0.214 g, 77% yield. Under solvent-free conditions (Table 2): 0.220 g, 79% yield. Yellow oil; R_f = 0.7 (silica gel, 90:10 hexane/EtOAc); IR (neat) 2953, 2926, 2854, 1698, 1600, 1501, 1452, 1323, 1156, 838 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.75−3.73 (m, 4H), 2.67−2.58 (m, 4H), 2.20 (t, J = 8.0 Hz, 2H), 1.61−1.28 (m, 14H), 1.27 (s, 3H), 1.00−0.83 (m, 6H); ^{13}C{1H} NMR (100 MHz, $CDCl_3$) δ 84.4, 81.5, 67.4, 57.4, 47.0, 39.3, 32.2, 31.0, 28.8, 23.7, 23.6, 22.5, 22.1, 18.5, 14.0, 13.9; LCMS m/z 280 [M + 1]; anal. calcd for $C_{18}H_{33}NO$ C 77.36, H 11.90, N 5.01; found C 77.23, H 11.82, N 5.12.

*4-(1,5-Dicyclohexyl-2-methylpent-3-yn-2-yl)morpholine (**7ad**).* Using toluene as solvent (Table 2): 0.261 g, 79% yield. Under solvent-free conditions (Table 2): 0.271 g, 82% yield. Brown liquid; R_f = 0.6 (silica gel, 90:10 hexane/EtOAc); IR (neat) 2949, 2855, 2357, 2341, 1452, 1359, 1326, 1274, 1119, 1071, 1032 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.74 (t, J = 4.0 Hz, 4H), 2.66−2.61 (m, 4H), 2.22 (d, J = 4.0 Hz, 2H), 2.06−1.99 (m, 3H), 1.89−1.77 (m, 6H), 1.72−1.68 (m, 3H), 1.66−1.58 (m, 8H), 1.57−1.51 (m, 5H), 1.31 (s, 3H); ^{13}C{1H} NMR (100 MHz, $CDCl_3$) δ 84.0, 81.8, 67.5, 57.6, 47.2, 45.2, 39.3, 36.3, 34.6, 34.4, 32.0, 25.3, 24.9, 24.5; LCMS m/z 332 [M + 1]; anal. calcd for $C_{22}H_{37}NO$ C 79.70, H 11.2, N 4.22; found C 79.58, H 11.31, N 4.28.

*4-(2,4-Dicyclohexylbut-3-yn-2-yl)morpholine (**7ae**).* Using toluene as solvent (Table 2): 0.221 g, 73% yield. Under solvent-free conditions (Table 2): 0.239 g, 79% yield. Brown liquid; R_f = 0.6 (silica gel, 90:10 hexane/EtOAc); IR (neat) 2934, 2853, 2354, 2333, 1440, 1268, 1251, 1004, 792 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.72 (t, J = 4.0 Hz, 4H), 2.59 (q, J = 4.0 Hz, 2H), 2.17 (t, J = 8.0 Hz, 4H), 1.57−1.47 (m, 7H), 1.26−1.21 (m, 11H), 0.89−0.86 (m, 5H); ^{13}C{1H} NMR (100 MHz, $CDCl_3$) δ 84.5, 81.5, 67.4, 57.4, 47.0, 39.3, 31.9, 30.0, 29.6, 29.3, 29.1, 28.8, 24.0, 23.7, 22.7, 18.6, 14.1; LCMS m/z 304 [M + 1]; anal. calcd for $C_{20}H_{33}NO$ C 79.15, H 10.96, N 4.62; found C 79.23, H 10.85, N 4.56.

*4-(2,4-Diphenylbut-3-yn-2-yl)morpholine (**7af**).* Under solvent-free conditions (Table 2): 0.084 g, 29% yield. Brown liquid; R_f = 0.6 (silica gel, 95:5 hexane/EtOAc); IR (neat) 3068, 3024, 2954, 2870, 2810, 1498, 1456, 1396, 1254, 1122 1100, 1073, 1023 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.86−7.82 (m,2H), 7.62−7.59 (m,2H), 7.42−7.32 (m, 6H), 3.80−3.77 (m, 4H), 2.88−2.75 (m, 2H), 2.64−2.50 (m, 2H), 1.73 (s, 3H); ^{13}C{1H} NMR (100 MHz, $CDCl_3$) δ 144.8, 131.8, 128.3, 128.2, 128.1, 127.2, 126.6, 123.1, 88.2, 67.4, 63.4, 48.0, 30.5;

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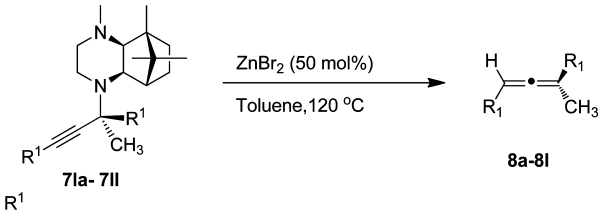
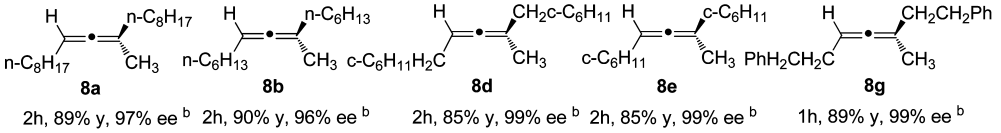
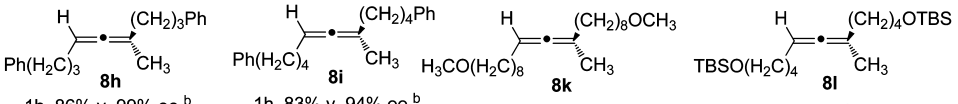
Table 6. $ZnBr_2$-Promoted Conversion of Chiral Propargylamines to Chiral Allenes[a]





2h, 89% y, 97% ee [b] 2h, 90% y, 96% ee [b] 2h, 85% y, 99% ee [b] 2h, 85% y, 99% ee [b] 1h, 89% y, 99% ee [b]



1h, 86% y, 99% ee [b] 1h, 83% y, 94% ee [b] 3h, 73% y, 90% ee [b] 2h, 68% y[c]

[a]The reactions were carried out by using propargylamine (1 mmol) which obtained from chiral amine **1l** in toluene (3 mL) with $ZnBr_2$ (0.5 mmol) at 120 °C. [b]Yield of allenes. The ee was determined by chiral HPLC analysis. [c]The ee could not be determined by chiral HPLC as the AD-H, AS-H, OB-H, OD-H, and OJ-H columns available to us failed to separate the enantiomers of **8l**.

LCMS *m/z* 292 [M + 1]; anal. calcd for $C_{20}H_{21}NO$ C 82.44, H 7.26, N 4.81; found C 82.28, H 7.31, N 4.73.

*4-(3-Methyl-1,7-diphenylhept-4-yn-3-yl)morpholine (**7ag**).* Using toluene as solvent (Table 2): 0.284 g, 82% yield. Under solvent-free conditions (Table 2): 0.295 g, 85% yield. Brown liquid; R_f = 0.6 (silica gel, 90:10 hexane/EtOAc); IR (neat) 3084, 3057, 3030, 2958, 2931, 2860, 1715, 1649, 1600, 1490, 1452, 1260, 1128, 1013 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.33−7.18 (m, 10H), 3.74 (t, *J* = 4.0 Hz, 4H), 2.87 (t, *J* = 8.0 Hz, 2H), 2.73 (t, *J* = 8.0 Hz, 2H), 2.64−2.55 (m, 6H), 1.92−1.88 (m, 2H), 1.35 (s, 3H); $^{13}C\{1H\}$ NMR (100 MHz, $CDCl_3$) δ 142.5, 140.7, 128.5, 128.3, 126.2, 125.7, 84.1, 82.2, 67.4, 57.4, 46.9, 41.1, 35.4, 30.5, 23.4, 20.7; LCMS *m/z* 349 [M + 1]; anal. calcd for $C_{24}H_{29}NO$ C 82.95, H 8.41, N 4.03; found C 82.84, H 8.47, N 4.07.

*4-(4-Methyl-1,9-diphenylnon-5-yn-4-yl)morpholine (**7ah**).* Using toluene as solvent (Table 2): 0.316 g, 84% yield. Under solvent-free conditions (Table 2): 0.307 g, 82% yield. Brown liquid; R_f = 0.6 (silica gel, 90:10 hexane/EtOAc); IR (neat) 2944, 2845, 1733, 1623, 1485, 1435, 1271, 935, cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.32−7.28 (m, 5H), 7.22−7.19 (m, 5H), 3.73 (t, *J* = 4.0 Hz 4H), 2.66−2.62 (m, 6H), 2.25 (t, *J* = 8.0 Hz, 2H), 1.80−1.73 (m, 3H), 1.64−1.56 (m, 5H), 1.27 (s, 3H); $^{13}C\{1H\}$ NMR (100 MHz, $CDCl_3$) δ 142.6, 142.4, 128.3, 128.2, 125.7, 125.6, 84.2, 81.7, 67.4, 57.4, 47.0, 39.1, 35.8, 35.3, 31.8, 30.5, 28.6, 23.8, 23.6, 18.4; LCMS *m/z* 376 [M + 1]; anal. calcd for $C_{26}H_{33}NO$ C 83.15, H 8.86, N 3.73; found C 83.05, H 8.81, N 3.68.

*4-(5-Methyl-1,11-diphenylundec-6-yn-5-yl)morpholine (**7ai**).* Using toluene as solvent (Table 2): 0.326 g, 81% yield. Under solvent-free conditions (Table 2): 0.313 g, 83% yield. Brown liquid; R_f = 0.6 (silica gel, 90:10 hexane/EtOAc); IR (neat) 3057, 3024, 2926, 2854, 1484, 1441, 1380, 1326, 1254, 1123, 1024, 964 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.32−7.28 (m, 5H), 7.22−7.19 (m, 5H), 3.73 (t, *J* = 4.0 Hz, 4H), 2.67−2.57 (m, 8H), 2.25 (t, *J* = 8.0 Hz, 2H), 1.76 (q, *J* = 8.0 Hz, 4H), 1.66−1.53 (m, 6H), 1.27 (s, 3H); $^{13}C\{1H\}$ NMR (100 MHz, $CDCl_3$) δ 142.6, 142.4, 128.3, 128.2, 125.7, 125.6, 84.2, 81.7, 67.4, 57.4, 47.0, 39.1, 35.8, 35.3, 31.8, 30.5, 28.6, 23.8, 23.6, 18.4; LCMS *m/z* 402 [M-1]; anal. calcd for $C_{28}H_{37}NO$ C 83.33, H 9.24, N 3.47; found C 83.15, H 9.32, N 3.41.

*7-Methyl-7-morpholinoundec-5-ynedinitrile (**7aj**).* Using toluene as solvent (Table 2): 0.202 g, 74% yield. Under solvent-free conditions (Table 2): 0.221 g, 81% yield. Brown liquid; R_f = 0.5 (silica gel, 70:30 hexane/EtOAc); IR (neat) 2942, 2857, 2363, 2242, 1714, 1666, 1454, 1425, 1283, 1115 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 3.73−3.71 (m, 4H), 2.58−2.57 (m, 4H), 2.51−2.47 (m, 2H), 2.43−2.37 (m, 4H), 1.89−1.84 (m, 2H), 1.80−1.76 (m, 4H), 1.29 (s, 3H); $^{13}C\{1H\}$ NMR (100 MHz, $CDCl_3$) δ 119.6, 119.1, 82.8, 82.2, 67.2, 60.3, 56.9, 47.0, 38.0, 24.7, 23.6, 21.0, 20.1, 17.1, 16.2, 14.1; LCMS *m/z* 274 [M + 1]; anal. calcd for $C_{16}H_{23}N_3O$ C 70.30, H 8.48, N 15.37; found C 70.21, H 8.41, N 15.26.

*4-(1,19-Dimethoxy-9-methylnonadec-10-yn-9-yl)morpholine (**7ak**).* Using toluene as solvent (Table 2): 0.291 g, 69% yield. Under solvent-free conditions (Table 2): 0.308 g, 73% yield. Brown liquid; R_f = 0.6 (silica gel, 85:15 hexane/EtOAc); IR (neat) 2926, 2853, 2363, 1708, 1456, 1383, 1273, 1118, 964, 863, 724 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 371 (t, *J* = 4.0 Hz 4H), 3.35 (t, *J* = 8.0 Hz, 4H), 3.31 (s, 6H), 2.58−2.57 (m, 4H), 2.1 (t,*J* = 8.0 Hz, 2H), 1.59−1.53 (m, 10H), 1.38−1.29 (m, 16H), 1.23 (s, 3H); $^{13}C\{1H\}$ NMR (100 MHz, $CDCl_3$) δ 84.4, 81.5, 72.9, 67.4, 58.5, 57.4, 47.0, 39.3, 29.9, 29.6, 29.5, 29.4, 29.1, 29.0, 28.7, 26.1, 26.0, 23.9, 23.8,18.5; LCMS *m/z* 424 [M + 1]; anal. calcd for $C_{26}H_{49}NO_3$ C 73.71, H 11.66, N 3.31; found C 73.65, H 11.61, N 3.36.

*4-(2,2,3,3,9,17,17,18,18-Nonamethyl-4,16-dioxa-3,17-disilanonadec-10-yn-9-yl)morpholine (**7al**).* Using toluene as solvent (Table 2): 0.316 g, 62% yield. Under solvent-free conditions (Table 2): 0.352 g, 69% yield. Brown liquid; R_f = 0.6 (silica gel, 95:5 hexane/EtOAc); IR (neat) 2920, 2854, 2356, 1720, 1643, 1457, 1172 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 3.69 (t, *J* = 4.0 Hz, 4H), 3.61 (t, *J* = 8.0 Hz, 4H), 2.60−2.56 (m, 4H), 2.19 (t, *J* = 8.0 Hz, 2H), 1.63−1.47 (m, 10H), 1.24 (s, 3H), 0.89 (s, 18H), 0.03 (s, 12H); $^{13}C\{1H\}$ NMR (100 MHz, $CDCl_3$) δ 84.3, 81.6, 67.4, 63.0, 62.7, 57.3, 47.0, 39.1, 33.1, 32.0, 25.9, 25.6, 23.8, 20.2, 18.4, 18.3, −5.2; LCMS *m/z* 512 [M + 1]; anal. calcd for $C_{28}H_{57}NO_3Si_2$ C 65.69, H 11.22, N 2.74; found C 65.58, H 11.06, N 2.81.

*1-(9-Methylnonadec-10-yn-9-yl)piperidine (**7ba**).* Using toluene as solvent (Table 2): 0.277 g, 77% yield. Under solvent-free conditions (Table 2): 0.292 g, 81% yield. Yellow oil; R_f = 0.6 (silica gel, 90:10 hexane/EtOAc); IR (neat) 3040, 2958, 2931, 2860, 1709, 1687, 1605, 1452, 1216, 1172 1024, 854 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 2.70−2.59 (m, 4H), 2.20 (t, *J* = 8.0 Hz, 2H), 1.78−1.58 (m, 6H), 1.49−1.29 (m, 29H), 0.90 (t, *J* = 8.0 Hz, 6H); $^{13}C\{1H\}$ NMR (100 MHz, $CDCl_3$) δ 83.6, 82.7, 57.8, 47.5, 39.7, 31.9, 31.8, 30.1, 29.5, 29.3,

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29.2, 29.1, 29.0, 28.8, 26.6, 24.8, 24.2, 24.0, 22.6, 18.6, 14.0; LCMS *m/z* 362 [M + 1]; anal. calcd for $C_{25}H_{47}N$ C 83.03, H 13.10, N 3.87; found C 82.91, H 13.15, N 3.81.

*1-Methyl-4-(9-methylnonadec-10-yn-9-yl)piperazine (**7ca**).* Using toluene as solvent (Table 2): 0.274 g, 73% yield. Under solvent-free conditions (Table 2): 0.300 g, 80% yield. Yellow oil; R_f = 0.7 (silica gel, 85:15 hexane/EtOAc); IR (neat) 3063, 2926, 2854, 2800, 2756, 1495, 1245, 1391, 1205, 1128, 1030, 745 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 2.79−2.42 (m, 8H), 2.29 (s, 3H), 2.18 (t, J = 8.0 Hz, 3H), 1.58−1.39 (m, 9H), 1.35−1.28 (m, 19H), 0.90 (s, 6H); $^{13}C\{1H\}$ NMR (100 MHz, $CDCl_3$) δ 84.2, 81.9, 57.2, 55.7, 46.3, 45.9, 39.6, 31.9, 31.8, 30.0, 29.5, 29.3, 29.2, 29.1, 29.0, 28.8, 24.1, 23.9, 22.6, 18.6, 14.0; LCMS *m/z* 377 [M + 1]; anal. calcd for $C_{25}H_{48}N_2$ C 79.72, H 12.84, N 7.44; found C 79.62, H 12.76, N 7.51.

*1-(9-Methylnonadec-10-yn-9-yl)-4-phenylpiperazine (**7da**).* Using toluene as solvent (Table 2): 0.315 g, 72% yield. Under solvent-free conditions (Table 2): 0.337 g, 77% yield. Yellow oil; R_f = 0.6 (silica gel, 90:10 hexane/EtOAc); IR (neat) 3062, 3013, 2953, 2925, 2876, 2837, 1665, 1626, 1478, 1391, 1369, 1237, 1117, 1034, 1056 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.31−7.27 (m, 2H), 6.98−6.87 (m, 3H), 3.24 (t, J = 8.0 Hz, 4H), 2.84−2.79 (m, 4H), 2.22 (t, J = 8.0 Hz, 4H), 1.67−1.65 (m, 3H), 1.54−1.38 (m, 9H), 1.34−1.29 (m, 15H), 0.93−0.90; $^{13}C\{1H\}$ NMR (100 MHz, $CDCl_3$) δ151.4, 129.0, 119.4, 115.8, 84.4, 81.8, 57.3, 49.5, 46.5, 43.8, 39.6, 31.9, 31.8, 30.1, 29.6, 29.3, 29.2, 29.1, 28.8, 24.1, 24.0, 23.8, 22.6, 18.6, 14.1; LCMS *m/z* 439 [M + 1]; anal. calcd for $C_{30}H_{50}N_2$ C 82.13, H 11.49, N 6.39; found C 82.21, H 11.36, N 6.45.

*1-Benzyl-4-(9-methylnonadec-10-yn-9-yl)piperazine (**7ea**).* Using toluene as solvent (Table 2): 0.357 g, 79% yield. Under solvent-free conditions (Table 2): 0.339 g, 75% yield. Yellow oil; R_f = 0.7 (silica gel, 95:5 hexane/EtOAc); IR (neat) 3024, 2953, 2854, 1604, 1583, 1489, 1451, 1325, 1259, 1128, 1051, 728 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.35−7.28 (m, 5H), 3.5 (s, 2H), 2.70−2.53 (m, 8H), 2.19 (t, J = 8.0 Hz, 2H), 1.58−1.52 (m, 2H), 1.51−1.49 (m, 3H), 1.43−1.41 (m, 5H), 1.40−1.30 (m, 16H), 1.28 (s, 3H), 0.90 (t, J = 8.0 Hz, 6H); $^{13}C\{1H\}$ NMR (100 MHz, $CDCl_3$) δ 138.2, 129.2, 128.1, 126.9, 84.1, 82.2, 63.0, 57.3, 53.6, 46.4, 39.6, 31.9, 31.8, 30.0, 29.5, 29.3, 29.2, 29.1, 28.8, 24.2, 23.9, 22.6. 18.6, 14.0; LCMS *m/z* 451 [M − 1]; anal. calcd for $C_{31}H_{52}N_2$ C 82.24, H 11.58, N 6.19; found C 82.15, H 11.48, N 6.27.

*1-(9-Methylnonadec-10-yn-9-yl)piperidin-3-ol (**7fa**).* Using toluene as solvent (Table 2): 0.294 g, 78% yield. Under solvent-free conditions (Table 2): 0.312 g, 83% yield. Yellow oil; R_f = 0.7 (silica gel, 70:30 hexane/EtOAc); IR (neat) 3342, 2953, 2926, 2854, 1704, 1676, 1621, 1320, 1172, 1128, 1063, cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 3.81(brs, 1H), 2.73−2.35 (m, 6H), 2.16 (t, J = 8.0 Hz, 2H), 1.77−1.75 (m, 1H), 1.57−1.55 (m, 5H), 1.49−1.45 (m, 2H) 1.41−1.37 (m, 4H), 1.33−1.23 (m, 20H), 0.87 (t, J = 8.0 Hz, 6H) ; $^{13}C\{1H\}$ NMR (100 MHz, $CDCl_3$) δ 83.8, 82.3, 66.5, 57.3, 57.1, 54.0, 53.8, 47.2, 46.8, 39.8, 39.7, 32.0, 31.8, 30.0, 29.0, 28.8, 24.2, 24.0, 23.9, 22.6, 22.0, 18.5, 14.0; LCMS *m/z* 378 [M + 1]; anal. calcd for $C_{25}H_{47}NO$ C 79.51, H 12.54, N 3.71; found C 79.45, H 12.48, N 3.78.

*1-(((S)-1-((S)-9-methylnonadec-10-yn-9-yl)pyrrolidin-2-yl)-methyl)piperidine (**7ia**).* Using toluene as solvent: 0.199 g, 45% yield. Under solvent-free conditions (Table 2): 0.350 g, 79% yield. Brown oil; R_f = 0.6 (silica gel, 90:10 hexane/EtOAc); IR (neat) 2931, 2849, 2213, 1704, 1665, 1457, 1369, 1326, 1205, 1150, 1101, 1063, 991, 904, 734 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 3.30−3.25 (m, 2H), 2.94−2.92 (m, 2H), 2.72−2.54 (m,6H), 2.29−2.16 (m, 12H), 1.88 (d, J = 8.0 Hz, 2H), 1.75−1.70 (m,4H), 1.63−1.54 (m, 8H), 1.49−1.46 (m, 4H), 1.41−1.36 (m, 7H), 1.29 (s, 3H), 0.91−0.86 (m, 6H); $^{13}C\{1H\}$NMR (100 MHz, $CDCl_3$) δ 82.7, 82.6, 66.6, 58.8, 56.7, 55.3, 50.0, 41.4, 31.8, 31.3, 29.7, 29.5, 29.1, 28.4, 27.1, 25.8, 24.4, 24.1, 22.6, 18.6; LCMS *m/z* 445 [M + 1]; anal. calcd for $C_{30}H_{56}NO$ C 81.01, H 12.0, N 6.30; found C 81.12, H 12.61, N 6.21.

*(S)-3-Benzyl-4-((S)-9-methylnonadec-10-yn-9-yl)morpholine (**7ja**).* Using toluene as solvent (Table 3): 0.344 g, 76% yield. Under solvent-free conditions (Table 3): 0.394 g, 87% yield. Brown liquid; R_f = 0.8 (silica gel, 90:10 hexane/EtOAc); $[\alpha]_D^{25}$ −45.5 (*c* 0.62, $CHCl_3$); IR (neat) 3023, 2953, 2928, 2853, 2195,1601, 1495, 1455, 1366, 1274, 1120, 1079, 949, 894, 739 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.32−7.28 (m, 3H), 7.25−7.21 (m, 2H), 3.93 (d, J = 8.0 Hz 2H), 3.63 (t, J = 8.0 Hz 2H), 3.40−3.10 (m, 2H), 2.59 (d, J = 12.0 Hz, 2H), 2.22−2.19 (m, 1H), 1.66−1.53 (m, 6H), 1.50 (s, 3H), 1.42−1.30 (m, 10H), 0.95−0.88 (m, 6H); $^{13}C\{1H\}$ NMR (100 MHz, $CDCl_3$) δ 141.0, 129.4, 128.3, 125.6, 84.9, 83.8, 68.4, 68.0, 57.0, 55.9, 41.0, 40.1, 31.9, 31.8, 30.3, 30.1, 29.6, 29.3, 29.2, 29.1, 29.0, 28.9, 27.0, 24.2, 22.6, 18.7, 14.1, 14.0; LCMS *m/z* 454 [M + 1]; anal. calcd for $C_{31}H_{51}NO$ C 82.06, H 11.33, N 3.09; found C 82.16, H 11.26, N 3.15.

*(S)-3-Benzyl-4-((S)-7-methylpentadec-8-yn-7-yl)morpholine (**7jb**).* Using toluene as solvent (Table 3): 0.321 g, 81% yield. Under solvent-free conditions (Table 3): 0.341 g, 86% yield. Brown liquid; R_f = 0.8 (silica gel, 90:10 hexane/EtOAc); $[\alpha]_D^{25}$ −41.5 (*c* 0.69, $CHCl_3$); IR (neat) 3020, 2953, 2927, 2853, 2033, 1606, 1495, 1364, 1276, 1120, 1077, 955, 843, 739 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.31−7.17 (m, 5H), 3.95−3.37 (m, 2H), 3.23−3.10 (m, 2H), 2.65−2.42 (m, 3H), 2.22 (t, J = 8.0 Hz, 2H), 1.52−1.39 (m, 8H), 1.37−1.30 (m, 2H), 0.91−0.86 (m, 6H), 1.48 (s, 3H), 1.31−1.28 (m, 13H), 0.92−0.88 (m, 6H); $^{13}C\{1H\}$ NMR (100 MHz, $CDCl_3$) δ 140.9, 129.4, 128.4, 125.7, 84.6, 84.1, 68.5, 68.0, 56.8, 55.3, 41.7, 41.4, 31.9, 31.3, 30.0, 29.6, 29.0, 28.6, 24.5, 23.7, 22.7, 22.6, 18.7, 14.1, 14.0; LCMS *m/z* 398 [M − 1]; anal. calcd for $C_{27}H_{43}NO$ C 81.55, H 10.90, N 3.52; found C 81.46, H 10.82, N 3.48.

*(S)-3-Benzyl-4-((S)-6-methyltridec-7-yn-6-yl)morpholine (**7jc**).* Using toluene as solvent (Table 3): Yield: 0.287g, 78% Under solvent-free conditions (Table 3): 0.313 g, 85% yield. Brown liquid; R_f = 0.8 (silica gel, 90:10 hexane/EtOAc); $[\alpha]_D^{25}$ −39.5(*c* 0.36, $CHCl_3$); IR (neat) 3023, 2955, 2928, 2854, 2150,1601, 1455, 1366, 1273, 1120, 1079, 1029, 949, 802, 739 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.33−7.21 (m, 5H), 3.96−3.60 (m, 3H), 3.41−3.09 (m, 5H), 2.60−2.20 (m, 3H), 1.69−1.55 (m, 4H), 1.50 (s,H), 1.46−1.29 (m, 10H), 0.95−0.88 (m, 6H); $^{13}C\{1H\}$ NMR (100 MHz, $CDCl_3$) δ 140.9, 129.4, 128.4, 125.7, 84.7, 84.1, 68.5, 68.0, 56.8, 55.3, 41.7, 41.4, 32.1, 31.1, 30.0, 28.7, 24.5, 23.5, 22.7, 22.2, 18.7, 14.1, 14.0; LCMS *m/z* 368 [M − 1]; anal. calcd for $C_{25}H_{39}NO$ C 81.24, H 10.64, N 3.79; found C 81.14, H 10.56, N 3.86.

*(S)-3-Benzyl-4-((S)-2,4-dicyclohexylbut-3-yn-2-yl)morpholine (**7je**).* Using toluene as solvent (Table 3): 0.282 g, 72% yield. Under solvent-free conditions (Table 3): 0.310 g, 79% yield. Brown liquid; R_f = 0.8 (silica gel, 90:10 hexane/EtOAc); $[\alpha]_D^{25}$ −37.1 (*c* 0.56, $CHCl_3$); IR (neat) 2925, 2864, 1995, 1655, 1495, 1344, 1276, 1120, 1078, 1022, 974, 801, 740 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.30−7.28 (m, 2H), 7.25−7.20 (m, 3H) 3.94 (d, J = 8.0 Hz, 2H), 3.61 (t, J = 12.0 Hz, 2H), 3.42−3.13 (m, 2H), 2.60 (d, J = 8.0 Hz, 2H), 2.37−2.36 (m, 1H), 2.28−2.26 (m, 1H), 2.11−2.10 (m, 4H), 1.81−1.79 (m, 7H), 1.69−1.65 (m, 5H), 1.53 (s, 3H), 1.29−1.26 (m, 5H); $^{13}C\{1H\}$ NMR (100 MHz, $CDCl_3$) δ 141.2, 129.4, 128.4, 125.6, 89.3, 83.6, 68.6, 68.1, 58.6, 56.8, 45.0, 40.9, 33.1, 33.0, 29.3, 29.1, 27.4, 27.1, 26.3, 25.9, 24.8,19.4; LCMS *m/z* 394 [M + 1]; anal. calcd for $C_{27}H_{39}NO$ C 82.39, H 9.99, N 3.56; found C 82.45, H 9.91, N 3.61.

*(S)-3-Benzyl-4-((S)-2,4-diphenylbut-3-yn-2-yl)morpholine (**7jf**).* Under solvent-free conditions (Table 3): Yield: 0.087g, 23%. Brown liquid; R_f = 0.8 (silica gel, 90:10 hexane/EtOAc); $[\alpha]_D^{25}$ −35.8 (*c* 0.74, $CHCl_3$); IR (neat) 3023, 2954, 2850, 2055, 1683, 1597, 1488, 1370, 1277, 1171, 1069, 975, 841, 755 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.89−7.87 (m, 3H), 7.56−7.54 (m, 2H), 7.39−7.32 (m, 10H), 3.82−3.76 (m, 2H), 3.65−3.62 (m, 2H), 3.41−3.35 (m, 2H), 2.64−2.52 (m, 1H), 2.21 (d, J = 8 Hz, 2H), 1.85 (s, 3H); $^{13}C\{1H\}$ NMR (100 MHz, $CDCl_3$) δ 146.8, 140.6, 131.5, 129.5, 128.5, 128.3, 128.2, 128.1, 127.1, 126.3, 125.9, 123.2, 91.6, 87.9, 68.7, 67.8, 61.5, 56.8, 42.9, 30.5, 30.3; LCMS *m/z* 380 [M − 1]; anal. calcd for $C_{27}H_{27}NO$ C 85.00, H 7.13, N 3.67; found C 85.12, H 7.18, N 3.75.

*(S)-3-Benzyl-4-((S)-4-methyl-1,9-diphenylnon-5-yn-4-yl)-morpholine (**7jh**).* Using toluene as solvent (Table 3): 0.330 g, 71% yield. Under solvent-free conditions (Table 3): 0.385 g, 83% yield. Brown liquid; R_f = 0.8 (silica gel, 90:10 hexane/EtOAc); $[\alpha]_D^{25}$ −41.3 (*c* 0.59, $CHCl_3$); IR (neat) 3024, 2944, 2852, 1954, 1663, 1495, 1370, 1274, 1119,1080, 950, 834, 741 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.36−7.30 (m, 7H), 7.28−7.24 (m, 8H), 3.95 (d, J = 4.0 Hz 2H), 3.65 (d, J = 4.0 Hz 2H), 3.43−3.39 (m, 2H), 2.79−2.75 (m, 2H), 2.71−

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2.66 (m, 2H), 2.54−2.51 (m, 2H), 2.29−2.25 (m, 3H), 1.90−1.79 (m, 6H), 1.55 (s, 3H); ^{13}C{1H} NMR (100 MHz, $CDCl_3$) δ 142.5, 141.7, 140.8, 129.4, 128.5, 128.4, 128.3, 125.8,125.7, 84.6, 84.2, 68.5, 67.9, 56.8, 55.2, 41.4, 41.1, 36.0, 34.9, 30.7, 30.1, 25.6, 24.6, 18.2; LCMS *m*/*z* 466 [M + 1]; anal. calcd for $C_{33}H_{39}NO$ C 85.11, H 8.44, N 3.01; found C 85.03, H 8.49, N 3.18.

(S)-7-((S)-3-Benzylmorpholino)-7-methylundec-5-ynedinitrile ***(7jj)***. Using toluene as solvent (Table 3): 0.250 g, 69% yield. Under solvent-free conditions (Table 3): 0.261 g, 72% yield. Brown liquid; R_f = 0.6 (silica gel, 60:40 hexane/EtOAc); $[\alpha]_D^{25}$ −37.9 (*c* 0.51, $CHCl_3$); IR (neat) 2956, 2854, 2244, 1601, 1454, 1274, 1173, 1081, 1029, 950, 866, 735 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.33−7.29 (m, 2H), 7.28−7.23 (m, 3H), 3.94 (d, *J* = 8.0 Hz 2H), 3.61 (t, *J* = 12.0 Hz, 2H), 3.25−3.21 (m, 2H), 2.55−2.50 (m, 7H), 2.19−2.11 (m, 2H), 1.94−1.87 (m, 6H), 1.43 (s, 3H); ^{13}C{1H} NMR (100 MHz, $CDCl_3$) δ 140.1, 129.3, 128.5, 126.0, 119.6, 118.9, 85.2, 82.4, 68.4, 67.7, 56.7, 54.8, 41.4, 40.3, 29.9, 24.7, 24.3, 20.0, 17.9, 17.3, 16.3; LCMS *m*/*z* 364 [M + 1]; anal. calcd for $C_{23}H_{29}N_3O$ C 76.00, H 8.04, N 11.56; found C 76.15, H 8.12, N 11.65.

(S)-3-Benzyl-4-((S)-1,19-dimethoxy-9-methylnonadec-10-yn-9-yl)morpholine ***(7jk)***. Using toluene as solvent (Table 3): 0.425 g, 83% yield. Under solvent-free conditions (Table 3): 0.456 g, 89% yield. Brown liquid; R_f = 0.8 (silica gel, 90:10 hexane/EtOAc); $[\alpha]_D^{25}$ −29.3 (*c* 0.47, $CHCl_3$); IR (neat) 2925, 2852, 2201, 1718, 1658, 1455, 1356, 1274, 1173, 1029, 973, 843, 741 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.30−7.17 (m, 5H), 3.92 (d, *J* = 4.0 Hz, 2H), 3.59 (t, *J* = 8.0, 2H), 3.38−3.35 (m, 2H), 3.33 (s, 3H), 3.32 (s, 3H), 3.21−3.05 (m, 4H), 2.55 (d, *J* = 12.0 Hz, 2H), 2.43−2.39 (m, 1H), 2.18 (t, *J* = 8.0, 2H), 1.58−1.50 (m, 10H), 1.46 (s, 3H), 1.30−1.27 (m, 16H); ^{13}C{1H} NMR (100 MHz, $CDCl_3$) δ 140.9, 129.3, 128.3, 125.7, 84.6, 84.1, 72.9, 72.8, 68.5, 68.0, 58.5, 56.8, 55.2, 43.7, 41.7, 41.3, 29.9, 29.8, 29.6, 29.5, 29.4, 29.3, 29.2, 29.0, 28.9, 28.8, 26.1, 26.0, 24.5, 23.8, 18.6; LCMS *m*/*z* 514 [M + 1]; anal. calcd for $C_{33}H_{55}NO_3$ C 77.14, H 10.79, N 2.73; found C 77.26, H 10.72, N 2.71.

(4aS,5R,8S,8aR)-4,5,9,9-Tetramethyl-1-((S)-9-methylnonadec-10-yn-9-yl)decahydro-5,8-methanoquinoxaline ***(7la)***. Under solvent-free conditions (Table 5): 0.329 g, 68% yield. Yellow liquid; R_f = 0.6 (silica gel, 90:10 hexane/EtOAc); $[\alpha]_D^{25}$ −32.1 (*c* 0.42, $CHCl_3$); IR (neat) 2953, 2925, 2854, 2794, 1462, 1385, 1259, 1150, 1084, 1023, 855, 799, 710 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.09−2.95 (m, 2H), 2.49−2.40 (m, 4H), 2.27−2.21 (m, 4H), 2.14 (s, 3H), 1.64−1.51 (m, 8H), 1.31−1.24 (m, 20H), 1.19 (s, 3H), 0.99 (s, 3H), 0.90−0.87 (m, 10H), 0.79 (s, 3H); ^{13}C{1H} NMR (100 MHz, $CDCl_3$) δ 85.2, 81.1, 62.1, 60.1, 55.4, 55.1, 49.2, 49.0, 46.3, 44.1, 41.4, 36.9, 31.9, 31.8, 30.0, 29.6, 29.3, 29.1, 28.8, 27.2, 25.7, 23.8, 22.6, 22.0, 20.3, 18.6, 14.4, 14.1; LCMS *m*/*z* 486 [M + 2]; anal. calcd for $C_{33}H_{60}N_2$ C 81.75, H 12.47, N 5.78; found C 81.62, H 12.36, N 5.71.

(4aS,5R,8S,8aR)-4,5,9,9-Tetramethyl-1-((S)-7-methylpentadec-8-yn-7-yl)decahydro-5,8-methanoquinoxaline ***(7lb)***. Under solvent-free conditions (Table 5): 0.273 g, 64% yield. Yellow liquid; R_f = 0.6 (silica gel, 90:10 hexane/EtOAc); $[\alpha]_D^{25}$ −48.8 (*c* 0.13, $CHCl_3$); IR (neat) 2964, 2926, 2854, 2810, 1457, 1375, 1271, 1128, 958, 931, 860, 830, 750, 706 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.08−2.99 (m, 2H), 2.52−2.47 (d, *J* = 4.0 Hz, 1H), 2.25−2.16 (m, 7H), 1.73−1.49 (m, 8H), 1.30−1.26 (m, 17H), 1.17 (s, 3H), 1.12−1.07 (m, 1H), 0.99 (s, 3H), 0.90−0.88 (m, 7H), 0.78 (s, 3H); ^{13}C{1H}NMR (100 MHz, $CDCl_3$) δ 85.2, 81.1, 77.3, 62.1, 60.2, 55.4, 55.1, 49.2, 49.0, 46.3, 44.1, 41.4, 36.9, 31.8, 31.4, 29.6, 29.0, 28.5, 27.2, 25.7, 23.7, 22.6, 22.1, 20.3, 18.7, 14.4, 14.1; LCMS *m*/*z* 428 [M+]; anal. calcd for $C_{29}H_{52}N_2$ C 81.24, H 12.22, N 6.53; found C 81.06, H 12.15, N 6.45.

(4aS,5R,8S,8aR)-1-((S)-1,5-Dicyclohexyl-2-methylpent-3-yn-2-yl)-4,5,9,9-tetramethyldecahydro-5,8-methanoquinoxaline ***(7ld)***. Under solvent-free conditions (Table 5): 0.275 g, 61% yield. Yellow liquid; R_f = 0.6 (silica gel, 90:10 hexane/EtOAc); $[\alpha]_D^{25}$ −42.3 (*c* 0.39, $CHCl_3$); IR (neat) 2914, 2844, 2363, 1669, 1432, 1368, 1277, 1258, 1156, 745 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.45 (t, *J* = 8.0 Hz, 1H), 2.89−2.82 (m, 2H), 2.75−2.70 (m, 1H), 2.58−2.53 (m, 1H), 2.26 (s, 3H), 2.12−2.08 (m, 5H), 1.80−1.64 (m, 15H), 1.54−1.40 (m, 5H), 1.25 (s, 3H), 1.18−1.04 (m, 10H), 0.99 (s, 3H), 0.77 (s, 3H); ^{13}C{1H} NMR (100 MHz, $CDCl_3$) δ 82.9, 80.1, 78.7, 64.8, 54.7, 53.9, 50.0, 48.3, 47.4, 47.1, 41.8, 37.7, 37.4, 37.3, 34.2, 33.4, 33.2, 32.6, 31.2, 26.7, 26.5, 26.3, 26.2, 25.9, 22.1, 20.8, 14.6; LCMS *m*/*z* 452 [M + 2]; anal. calcd for $C_{31}H_{52}N_2$ C 82.24, H 11.58, N 6.19; found C 82.15, H 11.51, N 6.23.

(4aS,5R,8S,8aR)-1-((S)-2,4-Dicyclohexylbut-3-yn-2-yl)-4,5,9,9-tetramethyldecahydro-5,8-methanoquinoxaline ***(7le)***. Under solvent-free conditions (Table 5): 0.250 g, 59% yield. Yellow liquid; R_f = 0.6 (silica gel, 90:10 hexane/EtOAc); $[\alpha]_D^{25}$ −39.3 (*c* 0.52, $CHCl_3$); IR (neat) 2922, 2850, 1447, 1388, 1366, 1341, 1314, 1259, 1117, 1021, 965, 889, 804, 766 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.04−3.00 (m, 2H), 2.20 (s, 5H), 2.12 (s, 1H), 1.92−1.86 (m, 3H), 1.80−1.64 (m, 2H), 1.59−1.55 (m, 2H), 1.48−1.42 (m, 6H), 1.16 (s, 4H), 1.11 (s, 5H), 1.09 (s, 2H), 0.97 (s, 3H), 0.76 (s, 3H); ^{13}C{1H} NMR (100 MHz, $CDCl_3$) δ 85.6, 84.4, 77.4, 63.9, 61.8, 55.5, 55.2, 51.4, 49.2, 49.1, 46.3, 45.8, 43.7, 37.0, 33.2, 32.5, 29.6, 28.9, 28.4, 27.4, 27.1, 26.4, 26.0, 25.5, 24.7, 22.3, 22.0, 20.3, 14.4; LCMS *m*/*z* 425 [M + 1]; anal. calcd for $C_{29}H_{48}N_2$ C 82.01, H 11.39, N 6.60; found C 82.15, H 11.31, N 6.73.

(4aS,5R,8S,8aR)-4,5,9,9-Tetramethyl-1-((S)-3-methyl-1,7-diphenylhept-4-yn-3-yl)decahydro-5,8-methanoquinoxaline ***(7lg)***. Under solvent-free conditions (Table 5): 0.355 g, 76% yield. Yellow liquid; R_f = 0.6 (silica gel, 90:10 hexane/EtOAc); $[\alpha]_D^{25}$ −35.1 (*c* 0.39, $CHCl_3$); IR (neat) 3024, 2950, 2931, 2849, 1457, 1265, 1213, 1117, 1050, 915, 739, 701 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.34−7.28 (m, 6H), 7.24−7.19 (m, 4H), 3.16−3.10 (t, *J* = 8.0 Hz, 3H), 3.06−2.91 (m, 2H), 2.88−2.77 (m, 2H), 2.74−2.61 (m, 2H), 2.56−2.46 (m, 3H), 2.27−2.18 (m, 4H), 2.14−1.76 (m, 4H),1.65−1.58 (m, 2H), 1.39 (s, 3H), 1.24 (s, 3H), 1.19−1.09 (m, 2H) 1.03 (s, 3H), 0.82 (m, 3H); ^{13}C{1H} NMR (100 MHz, $CDCl_3$) δ 143.0, 140.8, 128.5, 128.4, 128.3, 126.2, 125.5, 85.5, 80.7, 62.0, 60.1, 55.4, 55.0, 49.3, 49.0, 46.4, 44.1, 43.4, 36.9, 35.4, 30.4, 29.3, 27.1, 25.6, 22.0, 20.7, 20.4, 14.4; LCMS *m*/*z* 469 [M + 1]; anal. calcd for $C_{33}H_{44}N_2$ C 84.56, H 9.46, N 5.98; found C 84.48, H 9.36, N 5.91.

(4aS,5R,8S,8aR)-4,5,9,9-Tetramethyl-1-((S)-4-methyl-1,9-diphenylnon-5-yn-4-yl)decahydro-5,8-methanoquinoxaline ***(7lh)***. Under solvent-free conditions (Table 5): 0.372 g, 75% yield. Yellow liquid; R_f = 0.6 (silica gel, 90:10 hexane/EtOAc); $[\alpha]_D^{25}$ −41.8 (*c* 0.53, $CHCl_3$); IR (neat) 3057, 3018, 2953, 2962, 2832, 1665, 1621, 1473, 1445, 1385, 1232, 1160, 760 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.34−7.27 (m, 5H), 7.24−7.19 (m, 5H), 2.90−2.88 (m, 3H), 2.77 (t, *J* = 8.0 Hz, 2H), 2.62 (t, *J* = 8.0 Hz, 2H), 2.29−2.16 (m, 6H), 1.85−1.46 (m, 13H), 1.29 (s, 3H), 1.03 (s, 3H), 0.93 (s, 3H), 0.81 (s, 3H); ^{13}C{1H} NMR (100 MHz, $CDCl_3$) δ 142.6, 141.8, 128.5, 128.5, 128.3, 128.2, 125.8, 125.6, 85.5, 80.8, 77.2, 62.1, 60.1, 55.3, 55.1, 49.2, 49.0, 46.3, 44.1, 40.9, 36.9, 36.1, 34.8, 30.7, 27.2, 25.7, 25.5, 22.0, 20.3, 18.1, 14.4; LCMS *m*/*z* 498 [M + 2]; anal. calcd for $C_{35}H_{48}N_2$ C 84.62, H 9.74, N 5.64; found C 84.56, H 9.71, N 5.58.

(4aS,5R,8S,8aR)-4,5,9,9-Tetramethyl-1-((S)-4-methyl-1,10-diphenyldec-5-yn-4-yl)decahydro-5,8-methanoquinoxaline ***(7li)***. Under solvent-free conditions (Table 5): 0.413 g, 79% yield. Yellow liquid; R_f = 0.6 (silica gel, 90:10 hexane/EtOAc); $[\alpha]_D^{25}$ −47.6 (*c* 0.56, $CHCl_3$); IR (neat) 3056, 3016, 2956, 2849, 1664, 1625, 1473, 1384, 1236, 1150, 739 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.32−7.21 (m, 10H), 2.92−2.81 (m, 4H), 2.66−2.52 (m, 5H), 2.34−2.26 (m, 8H), 1.79−1.70 (m, 7H), 1.36−1.29 (m, 12H), 1.04 (s, 3H), 0.81 (s, 3H); ^{13}C{1H} NMR (100 MHz, $CDCl_3$) δ 142.4, 128.4, 128.3, 125.7, 84.8, 78.2, 75.1, 65.3, 54.5, 50.1, 47.7, 47.5, 47.1, 46.5, 43.5, 37.3, 35.4, 30.4, 29.7, 28.6, 26.3, 22.2, 20.5, 18.5, 14.9; LCMS *m*/*z* 525 [M + 1]; anal. calcd for $C_{37}H_{52}N_2$ C 84.68, H 9.99, N 5.34; found C 84.49, H 9.91, N 5.26.

(4aS,5R,8S,8aR)-1-((S)-1,19-Dimethoxy-9-methylnonadec-10-yn-9-yl)-4,5,9,9-tetramethyldecahydro-5,8-methanoquinoxaline ***(7lk)***. Under solvent-free conditions (Table 5): 0.424 g, 78% yield. Yellow liquid; R_f = 0.6 (silica gel, 90:10 hexane/EtOAc); $[\alpha]_D^{25}$ −48.6 (*c* 0.61, $CHCl_3$); IR (neat) 2925, 2951, 2854, 1451, 1391, 1265, 1122, 1030, 910, 854, 730, 701 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.39−3.36 (m, 4H), 3.34 (s, 6H), 3.08−3.00 (m, 3H), 2.23 (s, 4H), 2.20−2.15 (m, 3H), 1.59−1.55 (m, 7H), 1.51−1.46 (m, 4H), 1.34−1.27 (m, 22H), 1.18 (s, 3H), 1.12−1.08 (m, 2H), 0.99 (s, 3H), 0.79 (s, 3H); ^{13}C{1H} NMR (100 MHz, $CDCl_3$) δ 85.2, 81.0, 77.1, 72.9, 62.1, 60.1,

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58.5, 55.4, 55.1, 49.2, 49.0, 46.3, 44.1, 41.3, 36.9, 29.9, 29.6, 29.5, 29.4, 29.3, 29.1, 29.0, 28.8, 27.2, 26.1, 25.6, 23.7, 22.0, 20.3, 18.6, 14.4; LCMS m/z 546 [M + 2]; anal. calcd for $C_{35}H_{64}N_2O_2$ C 77.15, H 11.84, N 5.14; found C 77.31, H 11.76, N 5.23.

*(4aS,5R,8S,8aR)-4,5,9,9-Tetramethyl-1-((S)-2,2,3,3,9,17,17,18,18-nonamethyl-4,16-dioxa-3,17-disilanonadec-10-yn-9-yl)decahydro-5,8-methanoquinoxaline (**7ll**).* Under solvent-free conditions (Table 5): 0.391 g, 62% yield. Yellow liquid; R_f = 0.6 (silica gel, 85:15 hexane/EtOAc); $[\alpha]_D^{25}$ −31.9 (c 0.73, $CHCl_3$) IR (neat) 2947, 2931, 2851, 2859, 2788, 1467, 1396, 1254, 1106, 832, 782 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 3.64−3.61 (m, 4H), 3.08−2.96 (m, 2H), 2.53−2.45 (m, 1H), 2.23−2.14 (m, 6H), 1.73−1.46 (m, 11H), 1.43−1.34 (m, 2H), 1.28 (s, 5H), 1.18 (s, 3H), 1.12−1.07 (m, 2H), 0.99 (s, 3H), 0.90 (s, 18H), 0.78 (s, 3H), 0.06 (s, 12H); $^{13}C\{1H\}$NMR (100 MHz, $CDCl_3$) δ 85.2, 81.0, 63.3, 62.7, 62.1, 60.1, 55.4, 55.1, 49.2, 49.0, 46.3, 44.0, 41.3, 36.9, 33.2, 32.0, 29.6, 27.2, 25.9, 25.6, 25.5, 22.0, 20.3, 20.2, 18.5, 18.3, 14.4, −5.2; LCMS m/z 634 [M + 2]; anal. calcd for $C_{37}H_{72}N_2O_2Si_2$ C 70.09, H 11.46, N 4.42; found C 70.27, H 11.37, N 4.36.

General Procedure for the Preparation of Chiral Allenes from Propargylamines. The chiral propargylamines **7** (1 mmol) were added to a stirred suspension of $ZnBr_2$ (0.113 g, 50 mol %) in dry toluene (3 mL), and the contents were refluxed for 1−3 h at 120 °C under a nitrogen atmosphere. Toluene was removed under reduced pressure, and the crude product was purified with silica gel (100−200 mesh) column chromatography using hexane/ethyl acetate as eluent to isolate the chiral allenes **8**.

*(R)-9-Methylnonadeca-9,10-diene (**8a**).* From chiral propargylamine **7ja**: 0.239 g, 86% yield, 96% ee; $[\alpha]_D^{25}$ −99.9 (c 0.51, $CHCl_3$). From chiral propargylamine **7la**: 0.247 g, 89% yield, 97% ee; $[\alpha]_D^{25}$ −101.5 (c 0.72, $CHCl_3$). Colorless liquid, R_f = 0.8 (silica gel, 100:0 hexane/EtOAc). The enantioselectivity was determined by HPLC using chiral column, chiralcel Phenomenex cellulose-1, 100:0 hexanes/i-PrOH; flow rate, 1.5 mL/min, 190 nm; retention times, 2.3 min (minor) and 3.5 min (major); IR (neat) 2958, 2926, 2854, 1961, 1468, 1380, 723 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 5.00 (s, 1H), 2.36 (s, 1H), 1.95−1.92 (m, 4H), 1.67−1.66 (t, J = 4.0 Hz, 3H), 1.40- 1.36 (m, 21H), 0.90−0.89 (m, 8H); $^{13}C\{1H\}$ NMR (100 MHz, $CDCl_3$) δ 201.1, 99.1, 90.0, 34.1, 31.8, 31.7, 29.4, 29.3, 29.0, 28.8, 27.5, 22.7, 19.3, 14.1; LCMS m/z 279 [M + 1]; anal. calcd for $C_{20}H_{38}$ C 86.25, H 13.75; found C 86.42, H 13.71.

*(−)-7-Methylpentadeca-7,8-diene (**8b**).* From chiral propargylamine **7jb**: 0.197 g, 89% yield, 90% ee; $[\alpha]_D^{25}$ −98.8 (c 0.42, $CHCl_3$). From chiral propargylamine **7lb**: 0.200 g, 90% yield, 96% ee; $[\alpha]_D^{25}$ −121.8 (c 0.56, $CHCl_3$). Colorless liquid, R_f = 0.8 (silica gel, 100:1 hexane/EtOAc). The enantioselectivity was determined by HPLC using chiral column, chiralcel OB-H, 90:10 hexanes/i-PrOH; flow rate, 0.3 mL/min, 190 nm; retention times, 10.3 min (major) and 13.3 min (minor); IR (neat) 2958, 2926, 2854, 1961, 1498, 1380, 723 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 5.00−4.97 (m, 1H), 1.99−1.91 (m, 4H), 1.68−1.58 (m, 3H), 1.44- 1.31 (m, 16H), 0.93−0.89 (m, 6H); $^{13}C\{1H\}$NMR (100 MHz, $CDCl_3$) δ 201.1, 99.1, 90.0, 34.1, 31.8, 31.7, 29.7, 29.4, 29.3, 29.0, 28.8, 27.5, 22.7, 19.3, 14.1; LCMS m/z 223 [M + 1]; anal. calcd for $C_{16}H_{30}$ C 86.40, H 13.60,; found C 86.28, H 13.51.

*(R)-(2-Methylpenta-2,3-diene-1,5-diyl)dicyclohexane (**8d**).* From chiral propargylamine **7ld**: 0.209 g, 85% yield, 99% ee; $[\alpha]_D^{25}$ −91.1 (c 0.39, $CHCl_3$). Colorless liquid, R_f = 0.9 (silica gel, 100:0 hexane/EtOAc). The enantioselectivity was determined by HPLC using chiral column, chiralcel OJ-H, 95:5 hexanes/i-PrOH; flow rate, 0.5 mL/min, 190 nm; retention times, 6.4 min (minor) and 8.1 min (major); IR (neat) 3059, 3030, 2923, 2853, 1965, 1605, 1495, 1454, 1263, 1074, 1019 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 4.90 (s, 1H), 1.86−1.80 (m, 3H), 1.71−1.63 (m, 10H), 1.4−1.18 (m, 10H), 0.89 (m, 6H); $^{13}C\{1H\}$ NMR (100 MHz, $CDCl_3$) δ 202.3, 96.5, 87.6, 42.3, 38.1, 37.5, 35.7, 33.4, 33.3, 33.1, 26.6, 26.3, 19.4; LCMS m/z 247 [M + 1]; anal. calcd for $C_{18}H_{30}$ C 87.73, H 12.27; found C 87.63, H 12.21.

*(R)-Buta-1,2-diene-1,3-diyldicyclohexane (**8e**).* From chiral propargylamine **7je**: 0.189 g, 87% yield, 99% ee; $[\alpha]_D^{25}$ −77.9 (c 0.42, $CHCl_3$). From chiral propargylamine **7le**: 0.187 g, 85% yield, 99% ee; $[\alpha]_D^{25}$ −76.8 (c 0.59, $CHCl_3$). Colorless liquid, R_f = 0.8 (silica gel, 100:0 hexane/EtOAc). The enantioselectivity was determined by HPLC using chiral column, chiralcel OJ-H, 95:5 hexanes/i-PrOH; flow rate, 0.5 mL/min, 190 nm; retention times, 6.4 min (major) and 8.2 min (minor); IR (neat) 2936, 2841, 2239, 1964, 1448, 1416, 1280, 1232, 840 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 5.02 (s, 1H), 1.90−1.67 (m, 12H), 1.26−1.22 (m, 9H), 1.14−1.00 (m, 4H); $^{13}C\{1H\}$ NMR (100 MHz, $CDCl_3$) δ 199.2, 105.3, 96.9, 41.6, 37.7, 33.3, 32.1, 32.0, 26.5, 26.4, 26.3, 26.1, 17.8; LCMS m/z 219 [M + 1]; anal. calcd for $C_{16}H_{26}$ C 88.00, H 12.0; found C 87.91, H 12.06.

*(R)-Buta-1,2-diene-1,3-diyldibenzene (**8f**).* From chiral propargylamine **7jf**: 0.146 g, 71% yield, 94% ee; $[\alpha]_D^{25}$ −962.3 (c 0.47, $CHCl_3$). Colorless liquid, R_f = 0.6 (silica gel, 97:3 hexane/EtOAc). The enantioselectivity was determined by HPLC using chiral column, chiralcel OB-H, 98:2 hexanes/i-PrOH; flow rate, 1.0 mL/min, 220 nm; retention times, 6.15 min (minor) and 7.05 min (major); IR (neat) 3060, 3027, 2955, 1936, 1597, 1493, 1452, 758 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.59−7.55 (m, 2H), 7.44−7.33 (m, 8H), 6.57 (s, 1H), 2.32 (s, 3H); $^{13}C\{1H\}$ NMR (100 MHz, $CDCl_3$) δ 206.8, 136.3, 134.5, 128.7, 128.4, 127.0, 126.9, 125.8, 104.5, 96.5, 16.7. The ^{13}C NMR data showed 1:1 correspondence with the reported data.

*(R)-(3-Methylhepta-3,4-diene-1,7-diyl)dibenzene (**8g**).* From chiral propargylamine **7lg**: 0.233 g, 89% yield, 99% ee; $[\alpha]_D^{25}$ −109.3 (c 0.45, $CHCl_3$). Colorless liquid, R_f = 0.9 (silica gel, 100:0 hexane/EtOAc). The enantioselectivity was determined by HPLC using chiral column, chiralcel chiralcel OJ-H, 100:0 hexanes/i-PrOH; flow rate, 0.5 mL/min, 214 nm; retention times, 11.8 min (major) and 16.1 min (minor); IR (neat) 3084, 3068, 3024, 2854, 1961, 1600, 1495, 1452, 1265, 1035, 745 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.31 (t, J = 8.0 Hz, 5H), 7.21 (d, J = 4.0 Hz, 5H), 5.14−5.10 (m, 1H), 2.69 (t, J = 8.0 Hz, 4H), 2.31−2.22 (m, 4H), 1.70 (s, 3H); $^{13}C\{1H\}$NMR (100 MHz, $CDCl_3$) δ 201.4, 142.2, 142.0, 128.4, 128.3, 128.1, 125.6, 99.4, 90.2, 35.6, 35.4, 33.8, 30.8, 19.3; LCMS m/z 263 [M + 1]; anal. calcd for $C_{20}H_{22}$ C 91.55, H 8.45; found C 91.45, H 8.53.

*(R)-(4-Methylnona-4,5-diene-1,9-diyl)dibenzene(**8h**).* From chiral propargylamine **7jh**: 0.243 g, 84% yield, 99% ee; $[\alpha]_D^{25}$ −85.9 (c 0.46, $CHCl_3$). From chiral propargylamine **7lh**: 0.251 g, 86% yield, 99% ee; $[\alpha]_D^{25}$ −85.5 (c 0.63, $CHCl_3$). Colorless liquid, R_f = 0.6 (silica gel, 100:0 hexane/EtOAc). The enantioselectivity was determined by HPLC using chiral column, chiralcel Phenomenex amylose-2, 100:0 hexanes/i-PrOH; flow rate, 0.5 mL/min, 190 nm; retention times, 8.1 min (major) and 11.7 min (minor); IR (neat) 2958, 2849, 1960, 1447, 1347, 1258, 986, 962, 889, 842 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.34−7.29 (m, 5H), 7.24−7.20 (m, 5H), 5.10 (s, 1H), 2.74 (t, J = 8.0 Hz, 2H), 2.68−2.64 (m, 3H), 2.23 (d of t J_1 = 8.0 Hz, J_2 = 2.6 Hz, 2H), 2.08−1.99 (m, 4H), 1.80−1.72 (m, 4H), 1.28 (t, J = 8.0 Hz, 1H); $^{13}C\{1H\}$ NMR (100 MHz, $CDCl_3$) δ 201.3, 142.6, 128.4, 128.2, 125.6, 99.1, 90.1, 35.4, 35.3, 33.5, 31.0, 29.3, 28.8, 19.4; LCMS m/z 291 [M + 1]; anal. calcd for $C_{22}H_{26}$ C 90.98, H 9.02; found C 90.82, H 9.08.

*(R)-(5-Methylundeca-5,6-diene-1,11-diyl)dibenzene(**8i**).* From chiral propargylamine **7li**: 0.263 g, 83% yield, 94% ee; $[\alpha]_D^{25}$ −97.2 (c 0.49, $CHCl_3$). Colorless liquid, R_f = 0.9 (silica gel, 100:0 hexane/EtOAc). The enantioselectivity was determined by HPLC using chiral column, chiralcel Phenomenex amylose-2, 100:0 hexanes/i-PrOH; flow rate, 1.0 mL/min, 190 nm; retention times, 3.7 min (major) and 5.2 min (minor); IR (neat) 2923, 2850, 1962, 1727, 1599, 1489, 1448, 1089, 1019, 810 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.30−7.27 (m, 5H), 7.26−7.18 (m, 5H), 5.06−4.96 (m, 1H), 2.65−2.58 (m, 5H), 2.23−2.19 (m, 2H), 1.97 (t, J = 8.0 Hz, 4H), 1.66−1.63 (m, 4H), 1.46 (s, 3H); $^{13}C\{1H\}$ NMR (100 MHz, $CDCl_3$) δ 201.2, 142.8, 128.4, 128.2, 125.6, 99.1, 90.0, 35.8, 33.9, 31.1, 29.2, 29.0, 28.8, 27.2, 19.3; LCMS m/z 319 [M + 1]; anal. calcd for $C_{24}H_{30}$ C 90.51, H 9.49; found C 90.65, H 9.39.

*(R)-5-Methylundeca-5,6-dienedinitrile(**8j**).* From chiral propargylamine **7jj**: 0.133 g, 71% yield, 99% ee; $[\alpha]_D^{25}$ −56.2 (c 0.35, $CHCl_3$). Colorless liquid, R_f = 0.6 (silica gel, 95:5 hexane/EtOAc). The enantioselectivity was determined by HPLC using chiral column, chiralcel AS-H, 100:0 hexanes/i-PrOH; flow rate, 0.3 mL/min, 190 nm; retention times, 13.0 min (minor) and 17.2 min (major); IR (neat) 3298, 2931, 2854, 2246, 1956, 1446, 1424, 1375, 1238 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 5.04 (m, 1H), 2.37 (q, J = 8.0 Hz,

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4H), 2.14−2.06 (m, 4H), 1.80−1.72 (m, 4H), 1.68 (s, 3H); $^{13}C\{1H\}$ NMR (100 MHz, $CDCl_3$) δ 201.5, 119.5, 98.6, 89.2, 32.5, 27.9, 24.7, 23.2, 19.1, 16.5, 16.4; LCMS m/z 188 [M + 1]; anal. calcd for $C_{12}H_{16}N_2$ C 76.55, H 8.57, N 14.88; found C 76.63, H 8.51, N 14.72.

*(R)-1,19-Dimethoxy-9-methylnonadeca-9,10-diene(**8k**).* From chiral propargylamine **7jk**: 0.229 g, 68% yield, 99% ee; $[\alpha]_D^{25}$ −92.3 (c 0.55, $CHCl_3$). From chiral propargylamine **7lk**: 0.246 g, 73% yield, 90% ee; $[\alpha]_D^{25}$ −79.1 (c 0.62, $CHCl_3$). Yellow oil, R_f = 0.7 (silica gel, 98:2 hexane/EtOAc). The enantioselectivity was determined by HPLC using chiral column, chiralcel OD-H, 100:0 hexanes/i-PrOH; flow rate, 1.0 mL/min, 190 nm; retention times, 6.0 min (major) and 9.2 min (minor); IR (neat) 2920, 2860, 1967, 1714, 1457, 1368, 1261, 1172, 745 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 4.97 (s, 1H), 3.41−3.32 (m, 10H), 1.95−1.88 (m, 3H), 1.65−1.64 (m, 3H), 1.61−1.52 (m, 4H), 1.42−1.30 (m, 20H); $^{13}C\{1H\}$ NMR (100 MHz, $CDCl_3$) δ 201.1, 99.1, 90.0, 72.9, 58.5, 34.1, 29.6, 29.5, 29.3, 29.2, 29.0, 27.5, 26.1, 19.3; LCMS m/z 339 [M + 1]; anal. calcd for $C_{22}H_{42}O_2$ C 78.05, H 12.5; found C 78.23, H 12.41.

*(R)-2,2,3,3,13,25,25,26,26-Nonamethyl-4,24-dioxa-3,25-disilaheptacosa-13,14-diene (**8l**).* From chiral propargylamine **7ll**: 0.289 g, 68% yield; $[\alpha]_D^{25}$ −66.3 (c 0.41, $CHCl_3$). Colorless liquid, R_f = 0.6 (silica gel, 97:3 hexane/EtOAc); IR (neat) 2958, 2936, 2806, 1715, 1473, 1260, 1095 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 5.0 (s, 1H), 3.63−3.59 (m, 4H), 2.21 (s, 3H), 1.98−1.95 (m, 4H), 1.66−1.52 (m, 4H), 1.46−1.26 (m, 4H), 0.89 (s, 18H), 0.05 (s, 12H); $^{13}C\{1H\}$ NMR (100 MHz, $CDCl_3$) δ 201.2, 99.2, 90.1, 84.5, 68.2, 63.1, 62.5, 33.8, 32.4, 32.3, 31.8, 31.5, 29.1, 25.9, 25.5, 24.9, 23.8,19.2, 18.3, 18.2, −5.20; LCMS m/z 427 [M + 1]; anal. calcd for $C_{24}H_{50}O_2Si_2$ C 67.54, H 11.81; found C 67.41, H 11.76.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.5b02554.

Copies of the ^1H and ^{13}C NMR spectra of the products, HPLC analysis profiles, X-ray data, and ORTEP diagram (PDF)

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Notes

The authors declare no competing financial interest.

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