Helical Structures

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One-Step Construction of Five Successive Rings by Rhodium-Catalyzed Intermolecular Double [2+2+2] Cycloaddition: Enantioenriched [9]Helicene-Like Molecules**

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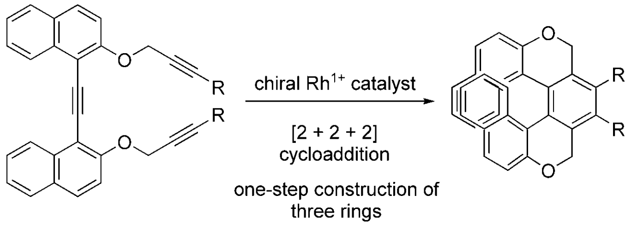
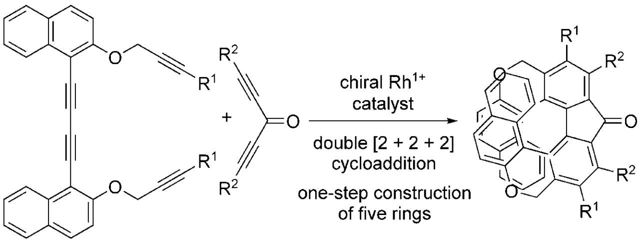
Helicenes and helicene-like molecules have long attracted much attention because of their potential applications to optical or electronic functional materials.[1] Therefore, flexible as well as convenient methods for their syntheses are highly desired for structural alterations and supply of sufficient quantities.[2] The most frequently employed method for the synthesis of helicenes is the oxidative photocyclization of stilbene-type precursors, however this procedure cannot be conducted on a large scale because of the highly dilute reaction conditions.[3] Several non-photochemical methods for the synthesis of [6]- and [7]helicenes and helicene-like molecules have been developed to date.[4] As such, transition metal mediated intramolecular [2+2+2] cycloadditions of triynes are useful methods for the synthesis of [6]- and [7]helicene-like molecules through the formation of three successive rings.[5,6] Stará and co-workers pioneered this strategy by using cobalt- or nickel-mediated or catalyzed [2+2+2] cycloadditions.[5] Following this pioneering work, we recently reported a cationic rhodium(I)/chiral bisphosphine complex, which catalyzed the intramolecular [2+2+2] cycloadditions of 2-naphthol-linked triynes, leading to enantioenriched [7]helicene-like molecules (Scheme 1).[6,7] Notably, non-photochemical methods that can furnish higher ordered ($\geq$[8]) helicenes and helicene-like molecules are rare.[8]



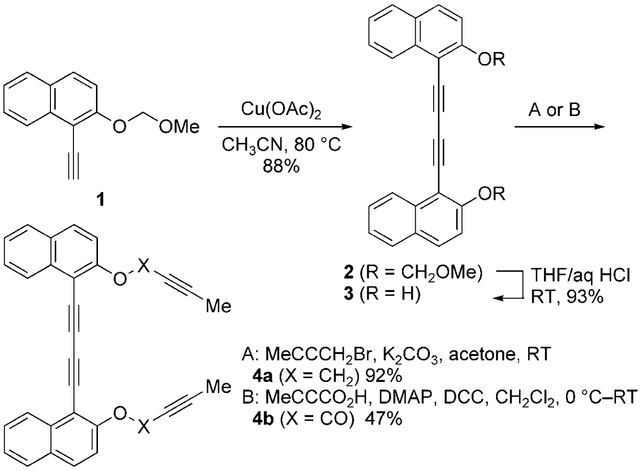
Scheme 1. Rhodium-catalyzed intramolecular [2+2+2] cycloaddition leading to enantioenriched [7]helicene-like molecules.

To access sterically more demanding [9]helicene-like molecules[9] starting from commercially available 2-naphthol, we designed an intermolecular double [2+2+2] cycloaddition between a 2-naphthol-linked tetrayne and a dialkynylketone,[10] which forms five successive rings (Scheme 2). This method would furnish various [9]helicene-like molecules, containing a densely substituted fluorenone core, by changing substituents of each cycloaddition partner.

The 2-naphthol-linked tetraynes **4** were readily prepared by a three-step sequence starting from a known terminal alkyne **1**[7] as shown in Scheme 3. A copper-mediated



Scheme 2. Rhodium-catalyzed intermolecular double [2+2+2] cycloaddition leading to enantioenriched [9]helicene-like molecules.



Scheme 3. Syntheses of tetraynes **4a** and **4b**. DMAP = 4-dimethylaminopyridine, DCC = dicyclohexylcarbodiimide.

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homocoupling of **1** and subsequent treatment with aqueous HCl furnished the 2-naphthol-substituted 1,3-diyne **3**. Etherification of **3** with 1-bromo-2-butyne gave the ether-linked tetrayne **4a**. Ester-linked tetrayne **4b** was also prepared by esterification of **3** with 2-butynoic acid.

Upon obtaining tetraynes **4a** and **4b**, we first investigated an intermolecular double [2+2+2] cycloaddition of the ether-linked tetrayne **4a** with dialkynylketone **5a** in the presence of cationic rhodium(I) complexes and various bis(phosphine) ligands (Figure 1). The study revealed that the use of 10 mol% of a $[Rh(cod)_2]BF_4$/(*R*)-segphos (cod = cycloocta-1,5-diene) complex at room temperature furnished the expected fluorenone-containing [9]helicene-like molecule **6aa** as a yellow solid in 56% yield upon isolation and 47% *ee* (Table 1, entry 1). In addition to **5a**, *n*-butyl- (Table 1, entry 2), phenyl- (Table 1, entry 3), and methoxymethyl substituted diethynylketones (Table 1, entries 4 and 5) participated in this reaction at room temperature by employing a cationic rhodium(I)/(*R*)-segphos or (*R*)-H_8-binap complex (10–20 mol%) as the catalyst.

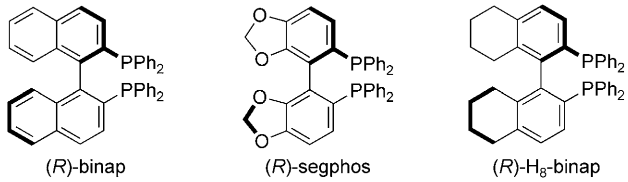
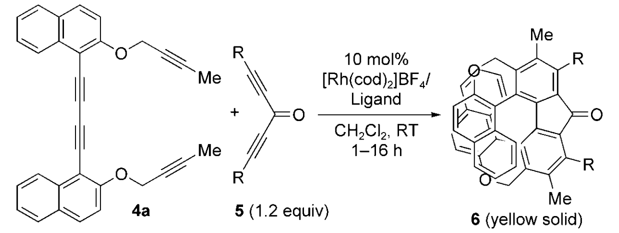


Figure 1. Structures of axially chiral biaryl bisphosphine ligands.

Table 1: Rhodium-catalyzed double [2+2+2] cycloadditions of tetrayne **4a** with diynes **5a–d**.

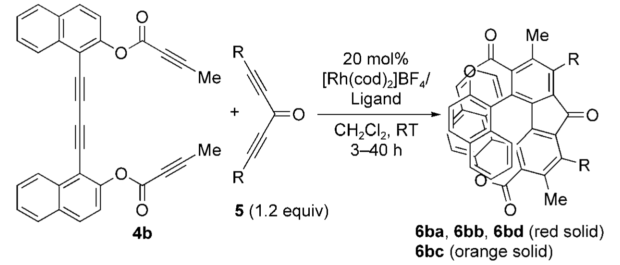


Entry	**5** (R)	Ligand	**6**	Yield [%][a] (*ee* [%])
1[b]	**5a** (Me)	(*R*)-segphos	(*P*)-(+)-**6aa**	56 (47)
2	**5b** (*n*Bu)	(*R*)-segphos	(+)-**6ab**	40 (39)
3	**5c** (Ph)	(*R*)-H_8-binap	(−)-**6ac**	53 (18)
4[c]	**5d** (CH_2OMe)	(*R*)-segphos	(+)-**6ad**	26 (26)
5[c]	**5d** (CH_2OMe)	(*R*)-H_8-binap	(−)-**6ad**	56 (10)

[a] Yield of isolated product. [b] **5a**: 2 equiv. [c] Catalyst: 20 mol%.

Next, an intermolecular double [2+2+2] cycloaddition of ester-linked tetrayne **4b** with **5a** was also investigated, revealing that the use of 20 mol% of a $[Rh(cod)_2]BF_4$/(*R*)-binap complex at room temperature furnished the expected fluorenone-containing [9]helicene-like molecule **6ba** as a red solid in 42% yield and 26% *ee* (Table 2, entry 1). The reactions of **4b** with *n*-butyl- (Table 2, entry 2) and phenyl-substituted diethynylketones (Table 2, entry 3) also proceeded by employing the cationic rhodium(I)/(*R*)-H_8-binap or (*R*)-segphos complex (20 mol%) as the catalyst. Although a high loading of the cationic rhodium(I)/(*R*)-segphos complex was required, the reaction of **4b** and methoxymethyl-substituted diethynylketone **5d** proceeded to yield the corresponding [9]helicene-like molecule **6bd** with the highest *ee* value (Table 2, entry 4).

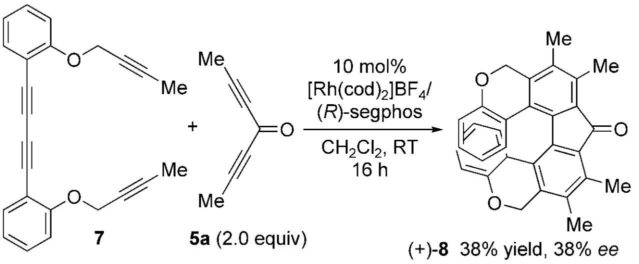
Table 2: Rhodium-catalyzed double [2+2+2] cycloadditions of tetrayne **4b** with diynes **5a–d**.



Entry	**5** (R)	Ligand	**6**	Yield [%][a] (*ee* [%])
1	**5a** (Me)	(*R*)-binap	(*P*)-(+)-**6ba**	42 (26)
2	**5b** (*n*Bu)	(*R*)-H_8-binap	(−)-**6bb**	58 (32)
3	**5c** (Ph)	(*R*)-segphos	(−)-**6bc**	61 (31)
4[b]	**5d** (CH_2OMe)	(*R*)-segphos	(+)-**6bd**	32 (60)

[a] Yield of isolated product. [b] Catalyst: 40 mol%. Solvent: $(CH_2Cl)_2$. Temperature: 40 °C.

As expected, fluorenone-containing [9]helicene-like molecules **6**, possessing large overlapping rings, did not undergo racemization at room temperature in CH_2Cl_2. In contrast, fluorenone-containing [7]helicene-like molecule **8**, which was prepared from phenol-linked tetrayne **7** and dialkynylketone **5a**, underwent gradual racemization under the same conditions (Scheme 4).



(+)-**8** 38% yield, 38% *ee*
(RT, 24 h in CH_2Cl_2: 22% *ee*)
(RT, 48 h in CH_2Cl_2: 13% *ee*)

Scheme 4. Synthesis and racemization of fluorenone-containing [7]helicene-like molecule **8**.

The enantiopure crystal of (*P*)-(+)-**6aa** was readily prepared by recrystallization (Figure 2).[11] The pseudohelical axes of [9]helicene-like molecules are nearly parallel to the *a*-axis (ca. 16.5°). The molecules that are related by the crystallographic 2_1-axes along the *c*-axis are packed almost parallel to the *bc*-plane. Adjacent molecular layers along the *a*-axis are related by the other 2_1-axes along the *b*-axis. Therefore, the helically chiral molecules are stacked in a partially overlapped fashion along the *a*-axis.

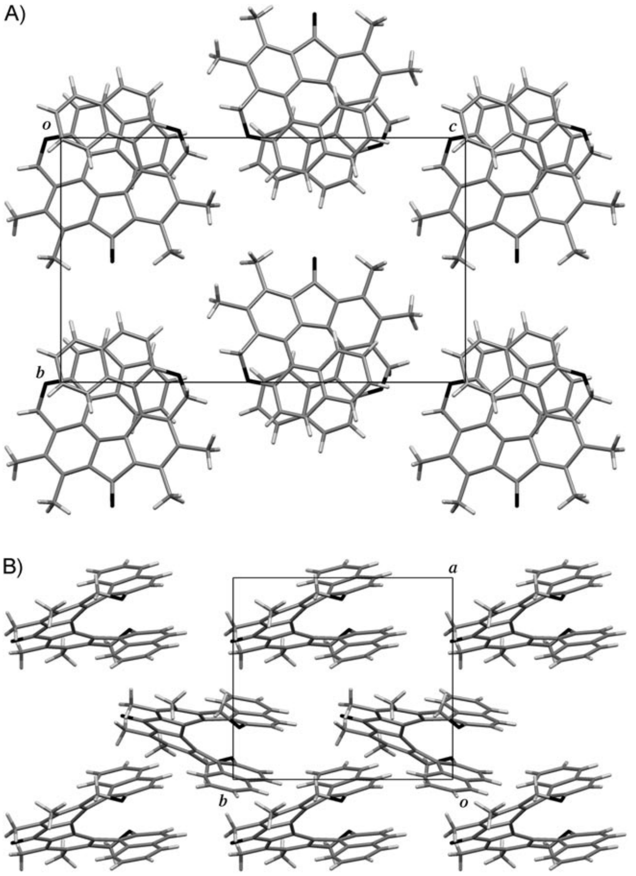


Figure 2. Packing structure of enantiopure (*P*)-(+)-**6aa**. A) *a*-projection view, B) *c*-projection view.

The enantiopure acetone solvate crystals of (*P*)-(+)-**6ba** was also readily prepared by recrystallization (Figure 3).[11] The pseudohelical axes of **6ba** are almost parallel to the *c*-axis (ca. 3.9°). The molecules that are related by crystallographic two-fold axes along the *b*-axis form a columnar structure. In this column, the fluorenone parts of the **6ba** molecules are stacked along the *c*-axis. In addition, intermolecular stacking between naphthalene rings was observed with an average ring separation of 3.415(2) Å.

Photophysical properties of helicene-like molecules **6** and **8** were briefly examined as shown in Table 3. As expected, highly conjugated ester-linked [9]helicene-like molecules **6ba–d** (Table 3, entries 5–8), containing two α-pyrone rings, exhibit larger optical rotation values than ether-linked [9]helicene-like molecules **6aa–d** (Table 3, entries 1–4). Interestingly, ether-linked [7]- and [9]helicene-like molecules **8** and **6aa** exhibit very close optical rotation values (Table 3, entries 1 and 9). In general, when the compounds possess two α-pyrone rings (Table 3, entries 5–8), bathochromic shifts in emission were observed when compared to **6aa–d** (Table 3, entries 1–4).

In conclusion, we have achieved the flexible and convenient syntheses of enantioenriched fluorenone-containing [9]helicene-like molecules by rhodium-catalyzed intermolecular double [2+2+2] cycloadditions. Their unique crystal structures and photophysical properties have also been determined. Future studies will focus on expanding the substrate scope including [11]helicene-like molecules and developing new materials by additional functionalization of these new helically chiral molecules.

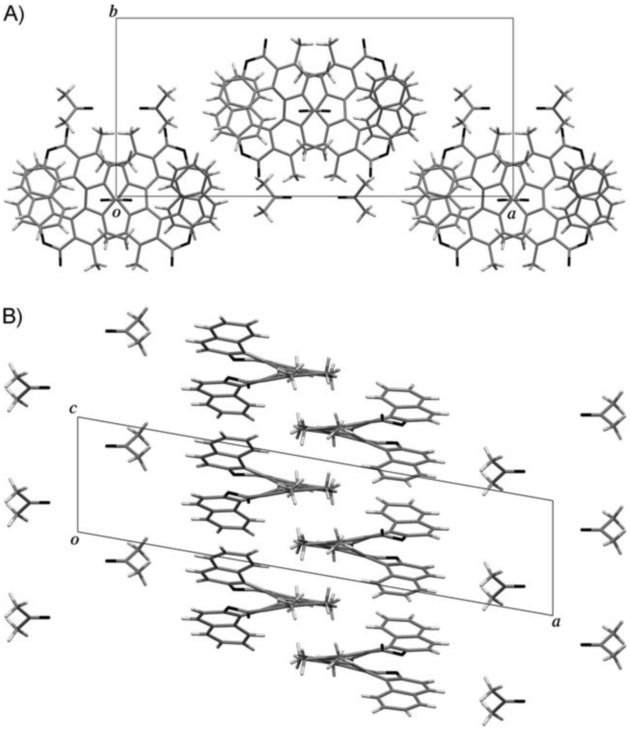


Figure 3. Packing structure of enantiopure (*P*)-(+)-**6ba**. A) *c*-projection view, B) *b*-projection view.

Table 3: Photophysical data of helicene-like molecule **6** and **8**.[a]

Entry	Compound	$[\alpha]_D^{25}$[b]	UV Absorption λ_{max} [nm][c]	Emission λ_{max} [nm]
1	(+)-**6aa**	1250	356	556
2	(+)-**6ab**	1499	357	554
3	(−)-**6ac**	1151	377	420, 444
4	(+)-**6ad**	1585	379	561
5	(+)-**6ba**	2050	313	580
6	(−)-**6bb**	1752	376	578
7	(−)-**6bc**	1605	341	423, 572
8	(+)-**6bd**	2033	381	472, 575
9	(+)-**8**	1245	349	559

[a] Measured in $CHCl_3$. [b] Values are calculated as 100% *ee*. [c] Only the longest absorption maximum wavelengths are given.

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[11] CCDC 727181 (**6aa**) and 727180 (**6ba**) 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.