Enantioselective Rhodium-Catalyzed Cycloisomerization of 1,6-Allenynes to access 5/6-Fused Bicycle[4.3.0]nonadienes

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Transition-metal-catalyzed cycloisomerization of 1,n-allenynes represents a powerful synthetic tool to rapidly assemble complex polycyclic skeletons from simple linear substrates. Nevertheless, there are no reports of the asymmetric version of these reactions. Moreover, most of these reactions proceed through a 6-endo-dig cyclization pathway, which preferentially delivers the distal product (via 5/5 rhodacyclic intermediate) rather than the proximal one (via 6/5 rhodacyclic intermediate). Herein, we report an enantioselective rhodium(I)-catalyzed cycloisomerization of 1,6-allenynes to provide the proximal product 5/6-fused bicycle[4.3.0]nonadienes in good yields and with excellent enantioselectivities. Remarkably, this chemistry works perfectly for 1,6-allenynes having a cyclic substituent within the allene component, thereby affording synthetically formidable tricyclic products with excellent enantioselectivities. Moreover, extensive DFT calculations suggest an uncommon pathway involving 5-exo-dig cycloisomerization, ring-expansion, rate-determining alkene isomerization involving Csp3-H activation, C-C activation of the cyclobutene moiety and finally reductive elimination. Deuterium labeling experiments support the rate-determining step involving the C-H bond activation in this transformation.
A pre-eminent goal of synthetic chemistry is the highly-selective construction of targeted structural complexity in an atom- and step-economy fashion. Transition metal-catalyzed cycloisomerization reactions of 1,α-allenynes provide a powerful synthetic approach in this regard, as they facilitate the rapid assembly of complex polycyclic skeletons from simple linear substrates. Since Malacria’s seminal work on the cobalt-catalyzed cycloisomerization of 1,α-allenynes, a variety of metals, such as Rh, Au, Pt, Ru, Pd, Co, Ti, Ag, Ga and Mo, have been reported to catalyze the reaction, which proceeds through the common metallacyclic or carbocation intermediate. Among these contributions, rhodium is of particular interest with respect to the selective C-H activation directed by the formation of metal–carbon bonds, thus giving cyclophanes in moderate to good yields. Mukai reported a similar rhodium(I)-catalyzed cycloisomerization of 1,α-allenynes A through Csp3–H12 and Csp2–H13–15 activation to furnish polycyclic products D efficiently (Fig. 1a). In addition, Mukai also reported a series of rhodium(I)-catalyzed cycloisomerization reactions of allenylcycloalkene-allenynes E (n = 1–3) through a metallacycle directed β-carbon elimination to access a variety of bicyclic products H (Fig. 1b)12,16-20. These reactions can be tentatively rationalized by the initial formation of the rhodacyclobutane[4,3,0] intermediate B/F, followed by the activation of the C–H and/or C-C bond proximal to the rhodium(I) center, which presumably collapses to the final products through reductive elimination12,20-23. Interestingly, C–H activation and C-C activation compete in some cases, which can be finely tuned by the careful selection of the rhodium(I) catalyst12,14. Although a diverse set of cycloisomerization reactions of 1,α-allenynes have been disclosed, to the best of our knowledge, there are no reports on the related asymmetric reactions. Additionally, all the examples involving rhodium(I)-catalyzed C–H and/or C-C activation of allenynes require no α-H at the allenic terminal of the substrate to prevent β-hydride elimination of the possible rhodacyclic intermediate B/F13,15–20,24,25.

As part of our continuing interests in asymmetric transition-metal-catalyzed cyclizations26–31, we now disclose an enantioselective rhodium(I)-catalyzed cycloisomerization of 1,α-allenynes through an unusual 5-exo-dig cyclization followed by an alkene isomerization via a Csp3–H activation process, which enables the synthesis of 5/6-fused bicyc[4.3.0]nonadienes in good yields and excellent enantioselectivities by careful selection of the chiral bisphosphine ligand (Fig. 1c). This work also represents a rare example of a reaction with substrates with α-H at the allenic terminal that favor Csp3–H activation rather than β-hydride elimination.

Results

Reaction optimization. Previous reports revealed that the intramolecular cycloisomerization of N-tethered 1,α-allenynes catalyzed by a rhodium(I) complex modified with a bidentate ligand provided the exclusive formation of the commonly observed Alder-ene product7–9,11,13,32–34. Since multiple factors, including the ancillary ligands, the counter-ions and the solvent can dramatically impact the course of rhodium(I)-catalyzed reactions11,35, there are significant opportunities to expand the synthetic possibilities for these highly reactive π-components, namely, 1,α-allenynes, towards the rhodium(I) catalyst by careful selection of reaction conditions2. We envisaged that rhodium(I)

![Fig. 1 Transition metal-catalyzed cycloisomerization of 1,α-allenynes.](https://example.com/f1.png)

**Fig. 1** Transition metal-catalyzed cycloisomerization of 1,α-allenynes. **a** Transition metal-catalyzed cycloisomerization of 1,α-allenynes involving C–H activation. **b** Transition metal-catalyzed cycloisomerization of 1,α-allenynes involving C-C activation. **c** This work: enantioselective rhodium(I)-catalyzed cycloisomerization of 1,6-allenynes to form proximal product 5/6-fused bicyc[4,3,0]nonadienes
species with a single vacant coordination site for the substrate would exhibit significantly different reactivity and selectivity\textsuperscript{36-38}. Therefore, we further investigated the influence of the rhodium(I) catalyst and solvent effects on the reaction. Treatment of 1a with the chiral rhodium(I) complex generated in situ from [Rh(CH\textsubscript{2}CH\textsubscript{2})\textsubscript{2}Cl\textsubscript{2}] (5 mol\%) and various chiral diphosphines (10 mol\%) and PPh\textsubscript{3} (10 mol\%) in the presence of silver salt (20 mol\%) in degassed 1,2-dichloroethane at room temperature indicates that the product distribution is highly ligand-dependent (Table 1 entries 1–4). For instance, L1-L3 furnished the commonly observed Alder-ene type product 3a exclusively (entries 1, 2, 3), whereas the highly strained and electron-rich C2-symmetric biarylphosphane ligand L4 furnished the unexpected 5/6-fused cycloadduct 2a, along with 3a in moderate yield, albeit with poor enantio-induction (entry 4). This result motivated further investigations to improve regio- and enantioselectivity of the reaction. Interestingly, replacing the pre-catalyst [Rh(CH\textsubscript{2}CH\textsubscript{2})\textsubscript{2}Cl\textsubscript{2}] to a cationic (entry 5) and neutral rhodium(I) precursor (entry 6) were inefficient, either leading to no conversion or the exclusive formation of 3a. Gratifyingly, the examination of the solvent on product formation and distribution led to significant improvements. For instance, 1,4-dioxane gave encouraging regio- and enantio-induction (entries 10 and 11), whereas other solvents, such as CHCl\textsubscript{3}, toluene, THF, were inferior (entries 7–9). Similar solvent effects were also observed by Sato and coworkers in their investigation of the ruthenium(I)-catalyzed cyclization of 1,6-allenynes\textsuperscript{39}. Moreover, closer examination of the influence of silver salts revealed that counter-ions exerted negligible effects on the reaction outcomes. Subsequent screening of monodentate ligands demonstrated that PCy3 delivered the desired 2a in good yield, along with satisfactory regioselectivity and excellent enantioselectivity (entry 12). Additionally, the reaction proceeds smoothly in the absence of an additional monodentate ligand, albeit with modest regio-selection. This suggests that additional ligand is not necessary for the reaction, whereas it improves the regio- and enantiocontrol. Finally, control experiments demonstrated that AgBF\textsubscript{4} did not catalyze the cyclization in the absence of rhodium, thereby indicating a rhodium-specific reaction.

**Substrate scope.** In light of the promising preliminary results with the optimal catalyst system (Table 1, entry 12), we selected to examine the scope and limitations of this rhodium(I)-catalyzed cycloisomerization of 1,6-allenynes (Table 2). For N-tethered substrates, the reactions are sensitive to the substituent on the

### Table 1 Reaction development and optimizations

| Entry<sup>a</sup> | [MX] | Ligand 1 | Solvent | Yield<sup>b</sup> | 2a:3a<sup>c</sup> | ee (%)<sup>d</sup> |
|------------------|--------|----------|--------|-----------------|-----------------|-----------------|
| 1                | [Rh(CH\textsubscript{2}CH\textsubscript{2})\textsubscript{2}Cl\textsubscript{2}] | L.1     | DCE    | 88              | 0:100           | -               |
| 2                | [Rh(CH\textsubscript{2}CH\textsubscript{2})\textsubscript{2}Cl\textsubscript{2}] | L.2     | DCE    | 36              | 0:100           | -               |
| 3                | [Rh(CH\textsubscript{2}CH\textsubscript{2})\textsubscript{2}Cl\textsubscript{2}] | L.3     | DCE    | 94              | 0:100           | -               |
| 4                | [Rh(CH\textsubscript{2}CH\textsubscript{2})\textsubscript{2}Cl\textsubscript{2}] | L.4     | DCE    | 76              | 32:68           | 39              |
| 5                | [Rh(NBD\textsubscript{2}BF\textsubscript{4})] | L.4     | DCE    | NR             | -               | -               |
| 6                | [Rh(NBD\textsubscript{2}Cl\textsubscript{2})] | L.4     | DCE    | 22              | 0:100           | -               |
| 7                | [Rh(CIL\textsubscript{2}Cl\textsubscript{2})] | L.4     | Toluene | 20              | 9:91           | 27              |
| 8                | [Rh(CH\textsubscript{2}CH\textsubscript{2})\textsubscript{2}Cl\textsubscript{2}] | L.4     | THF    | 10              | 10:90          | 24              |
| 9                | [Rh(CH\textsubscript{2}CH\textsubscript{2})\textsubscript{2}Cl\textsubscript{2}] | L.4     | CHCl\textsubscript{3} | 14              | 30:70          | 0               |
| 10               | [Rh(CH\textsubscript{2}CH\textsubscript{2})\textsubscript{2}Cl\textsubscript{2}] | L.4     | Dioxane<sup>e</sup> | 67              | 38:62          | 81              |
| 11               | [Rh(CH\textsubscript{2}CH\textsubscript{2})\textsubscript{2}Cl\textsubscript{2}] | L.5     | Dioxane<sup>e</sup> | 61              | 45:55          | 75              |
| 12<sup>a</sup>   | [Rh(CH\textsubscript{2}CH\textsubscript{2})\textsubscript{2}Cl\textsubscript{2}] | L.4     | Dioxane<sup>e</sup> | 82              | 85:15          | 90              |
| 13<sup>a</sup>   | [Rh(CH\textsubscript{2}CH\textsubscript{2})\textsubscript{2}Cl\textsubscript{2}] | L.4     | Dioxane<sup>e</sup> | 82              |              |                 |

NBD, norbornadiene; DCE, 1,2-dichloroethane; THF, tetrahydrofuran

<sup>a</sup>All the reactions were conducted with 1a (0.1 mmol) with an in situ generated ligand (10 mol\%)–PPh\textsubscript{3} (10 mol\%)–Rh(I) (5 mol\%) complex in the presence of Ag(I) salt (20 mol\%) in degassed solvent at 40 °C unless otherwise noted.

<sup>b</sup>The combined yield of 2a and 3a, isolated yields were reported.

<sup>c</sup>Determined by 1H-NMR of the mixture.

<sup>d</sup>Determined by HPLC using a chiral stationary phase. See Supplementary Figure 41.

<sup>e</sup>Without use of the additional ligand.

The bold values means the results under the optimal conditions.
alkyne terminus. All ortho-, meta- and para-substituted aryl groups are generally well tolerated (entries 1–8), affording the desired 5/6-fused cycloadducts in moderate to good yields with good to excellent enantioselectivities. Additionally, the aryl substitution pattern has an interesting impact on the reaction outcome. For example, electron-withdrawing groups proved to be beneficial to the yields, regio- and enantioselectivities (entries 1, 3, 4, 7 and 8), whereas electron-donating groups are detrimental (entries 2, 5 and 6). In addition, the 3-cyano aryl substituent led to low level of enantioinduction (entry 4), which may be attributed to the chelation to the rhodium center. Hetero-aryl groups on the alkyne terminus are also well tolerated (entry 10); however, N-tethered 1,6-allenynes with terminal alkynes (R = H, Supplementary Table 1, entry 3), or containing alkyl groups or other functional groups on the alkyne terminus (Supplementary Table 1, entries 1, 2 and 4), including O-tethered congeners (Supplementary Table 1, entries 5 and 6) afforded the exclusive formation of the Alder-ene type product, without any detectable amount of the corresponding 5/6-fused bicyclic product. These results indicate that the reaction is sensitive to the subtle changes in the nature of the tether and substituent. X-ray crystallographic analysis of 2g unambiguously established its structure possessing a bicycle[4.3.0]nonadiene framework with the absolute configuration of C8 having an S configuration.

Encouraged by aforementioned results, we wondered if the current catalytic system was also applicable to substrates with cyclic subunits within the allene component. Thus, several cyclic 1,6-allenynes were examined (Table 3). Gratifyingly, 1,6-allenynes both having a five-membered or a six-membered cyclic substituent within the allene proceed smoothly and provide improved results, thereby delivering the synthetically challenging tricyclic adducts 5 in high yields with excellent regio- and stereoselectivities (entries 1–4). In particular, the reactions displayed excellent diastereoselectivities (entries 1–4). For each example examined, only one diastereoisomer was detected by HPLC (400 MHz). The proposed relative stereochemical assignment of 5c was assigned based on the NOESY analysis (See Supplementary Figure 16).

**Table 2 Cycloisomerization of 1,6-allenynes**

| Entry | Substituents | Yield (%) | Ratio | ee (%) |
|-------|--------------|-----------|-------|--------|
| 1     | R = 2- F - C6H5 | 93        | 2b:3b = 73 : 27 | 89     |
| 2     | R = 3- Me - C6H5 | 82        | 2c:3c = 84 : 16 | 80     |
| 3     | R = 3- F - C6H5 | 86        | 2d:3d = 88 : 12 | 97     |
| 4     | R = 3- CN - C6H5 | 65        | 2e:3e = 95 : 5 | 45     |
| 5     | R = 4- Me - C6H5 | 89        | 2f:3f = 13 : 87 | 88     |
| 6     | R = 4- MeO - C6H5 | 81 | 2g : 3g = 80 : 20 | 78     |
| 7     | R = 4- Cl - C6H5 | 85        | 2h : 3h = 50 : 50 | 90     |
| 8     | R = 4- Br - C6H5 | 98        | 2i : 3i = 60 : 40 | 94     |
| 9     | R = 2- naphtyl | 52        | 2j : 3j = 45 : 55 | 55     |
| 10    | R = 2- thiophenyl | 65       | 2k : 3k = 40 : 60 | 92     |

*The reactions were conducted with 1 (0.1 mmol) with in situ generated complex with (S)-DTBM-BIPHEP (10 mol%), PCy3 (10 mol%), [(Rh(CH2CH2)2Cl)2]1 (5 mol%) in the presence of AgBF4 (20 mol %) in 1,4-dioxane at 40 °C unless otherwise noted.*

**Mechanistic studies.** To gain some insight into the reaction mechanism, we investigated the cyclization of [D6]-1a under the optimal reaction conditions (Table 1, entry 12). As expected, the reaction gave a mixture of the desired 5/6-fused bicyclic product [D6]-2a and Alder-ene type product [D6]-3a with the ratio of 1:1, wherein deuterium atom was transferred to the expected position in high content (Fig. 2a). In addition, a kinetic isotope competition experiment using an equimolar mixture of 1a and [D6]-1a by quenching at early stages (1–3 h) revealed that the reaction gave a mixture of 2a and [D6]-2a in 12–20% yield with the ratio of 68:32–73:27. The corresponding KIE was estimated to be ~2.5 (Fig. 2b). These results suggested that the rate-determining step probably involves C–H bond activation or formation.

To further understand the reaction mechanism of this unusual rhodium(I)-catalyzed cycloisomerization of 1,6-allenynes, an
extensive DFT (M06-L/6–31G* was used for the geometry optimization) study was conducted on seven possible pathways (i–vii) using the ligand L4, with PMe3 and substrate 1a (with 249 atoms in total). In addition, for the most possible pathway (i-Ph), PPh3 ligand was employed as opposed to PMe3 in order to draw a better comparison with the actual experimental results. Although the formation of the 5/6-fused bicycle[4.3.0]non-adienes and Alder-ene type products could be rationalized by the common initial oxidative cyclization pathways to form the rhoda (III)bicyclic intermediates (Fig.4), these common pathways were not supported by different DFT methods (M06-L, PW6B95-D3, B3LYP-D3, B3PW91-D3, BP86-D3, PBE0-D3 and ωB97XD methods for the energy calculations) due to their higher barriers (Figs. 3–5). As shown in Figs. 3–5, Supplementary Figures 56–62 and Table 4, our computational results emerged a uncommon pathway that the most favorable pathway starts from a stable rhodium(I) complex APh (Fig. 3 and Fig. 4)[40], in which the two phosphine atoms of L4 and a PPh3 ligand as well as the alkyne moiety of 1a coordinate to the acidic rhodium(I) metal. Then, the cationic metal complex APh preferentially undergoes 5-exo-dig cyclization with two new C-C bond formations to give a stable rhodium(I)-carbenoid complex BPhR (ΔG = −2.9 kcal/mol) with a barrier of about 22.4 kcal/mol in solution by the M06-L method. The similar computed barrier was also obtained from different DFT methods (~22.4–25.8 kcal/mol, Table 4). The 5-exo-dig cyclization is subsequently followed by a ring expansion to form a more stable bicyclic intermediate CPh (formal [2+2] cycloaddition product)11,12,36,41–44. Such transformation is (partly) analogous to Pt/Au-catalyzed cycloisomerization of allenynes23,35,36,41–44. After dissociation of the bulky PPh3 ligand from CPh and shift of another rhodium(I)-alkene coordination mode to form D′ (ΔG = −14.8 kcal/mol), isomerization of this alkene part from the methylethylidene moiety proceed. This Rh(I)-catalyzed isomerization involves oxidative addition through TS′D,E to give an unstable η3-allyl rhodium(III)-hydride intermediate E′ (ΔG = 0.7 kcal/mol). Such Rh(I)-mediated allylic Csp3–H activation was also proposed to be involved in another Rh(I)-catalyzed cycloisomerization reactions[40,45,46]. Notably, this Rh(I)-catalyzed Csp3–H
 activation (oxidative addition) process is different from the common pathway involving β-hydride elimination from rhoda (III)bicyclic intermediates (see Fig. 1 and 4). Then, the rate-determining rhodium(III)-mediated allylic C\textsubscript{sp3}-H bond-forming reductive elimination via TS\textsubscript{E,F} takes place to give rhodium(I) intermediates F' and G' with an overall barrier of ~29.5 kcal/mol above D'. Such isomerization transforms intermediate D' with the tetrasubstituted alkene moieties into intermediate F' and G' with the disubstituted alkene moieties. The alkene isomerization step is followed by the rhodium(I)-catalyzed C-C bond

**Fig. 3** DFT Results. The computed free energy profiles for the most possible pathway (i-Ph) of the Rh(I)-catalyzed cycloisomerization of 1,6-allyne (1a) in solution by SMD M06-L//M06-L method

**Table 4** The relative free energies (in kcal/mol) of the most possible pathway (i-Ph) and the barrier for the lowest-energy side-reaction oxidative coupling pathway (via TS\textsubscript{P-Q}) for the Rh(I)-catalyzed cycloisomerization of a 1,6-allene (1a) in solution phase by different DFT methods (except PW6B95-D3 in gas phase). PPh\textsubscript{3} was used as the additional ligand
methods are also given in parenthesis and bracket, respectively. The SMD M06-L//M06-L method. The relative free energy for the key activation process involving rhodium(I)-catalyzed oxidative regeneration of a cationic Rh(I) complex. The overall process was computed to be exergonic by about 55.1 kcal/mol in solution.

In general, different DFT methods give a qualitatively similar agreement with our KIE experiments (Fig. 2). This mechanism involving the uncommon 5-exo-dig cyclization, rhodium(I)-catalyzed C–H bond activation and C–C bond activation steps was proposed to be the key factor to form the unusual 5/6-fused bicycle[4.3.0]nonadienes.

In comparison, different DFT methods also show that the lowest-energy side-reaction oxidative coupling pathway (via $T_{Sp}$, $Q$) generally has a larger barrier than that for the above-mentioned 5-exo-dig cyclization via $T_{SpH}$-$B$($R$). These computational results demonstrated that the second PPh$_3$ ligand play a critical role in directing the reaction towards the initial 5-exo-dig cyclization step and suppressing the common initial oxidative coupling pathway. In the absence of the PPh$_3$ ligand, 1,4-dioxane molecule might coordinate to the rhodium(I) metal center and thus disfavor the oxidative coupling pathway to form the Alderene type product.

The overall reaction mechanism for the most favorable pathway is slightly different, when a smaller PMe$_3$ ligand was used to replace PPh$_3$ as the monodentate ligand. Notably, the computed barrier for the 5-exo-dig cyclization with the PMe$_3$ ligand is quite similar (22.8 kcal/mol); however, the bulky PPh$_3$ ligand is only involved in the first stage of the cycloisomerization and then dissociates from the metal, presumably due to steric repulsion with the bulky L4 ligand and substrate. In contrast, PMe$_3$ can re-coordinate to the metal center in the key $C_{sp3}$–$H$ bond-forming reductive elimination step. In comparison, our DFT results show that the common pathways (such as initial 6-endo-dig cyclization (pathway iii), initial oxidative coupling between the alkyne and allene parts (pathways ii and iv), initial $C_{sp3}$–$H$ activation (pathways v and vi) and initial single C–C bond forming (pathway vii), see Fig. 5) were computed to have higher barriers than the 5-exo-dig cyclization via $T_{SpH}$-$B$($R$) in the most favorable pathway (i), presumably due to a stronger binding affinity of PMe$_3$ than the alkene and a more bulky ligand L4 disfavoring the above-mentioned common pathways. Our proposed most favorable pathway was also supported by different DFT methods (Supplementary Tables 2–27). Moreover, our DFT calculations also suggest that the alkene isomerization step with the new C–H bond formation is the possible rate-determining step.

**Fig. 4** The mechanistic pathways. The common pathway and our proposed pathway for the uncommon formation of 5/6-Fused Bicycle[4.3.0]nonadienes.

**Fig. 5** Computational studies on several pathways. The free energy profiles for different reaction pathways of the cationic Rh(I)-catalyzed cycloisomerization of 1,6-allenyl (1a) using a PMe$_3$ ligand in solution by the SMD M06-L//M06-L method. The relative free energy for the key transition states by SMD PBE0-D3//M06-L and SMD B3LYP-D3//M06-L methods are also given in parenthesis and bracket, respectively.

activation of the cyclobutene moiety of $G'$ via $T_{SpG}$-$H$ to give a stable rhodacycle intermediate $H'$ by overcoming the barrier of roughly 26.4 kcal/mol above $G'$. Again, such C–C bond activation process involving rhodium(I)-catalyzed oxidative addition is also different from that in the common pathways involving the rhoda[II]bicyclic intermediates (Fig. 1 and 4). Finally, C–C forming reductive elimination completes the reaction to afford the desired 5/6-fused bicyclic product $I'$ with regeneration of a cationic Rh(I) complex. The overall process was computed to be exergonic by about 55.1 kcal/mol in solution. In general, different DFT methods give a qualitatively similar mechanistic picture and suggest the highest overall barrier for the $C_{sp3}$–$H$ bond-forming reductive elimination, which is in
Discussion

In summary, this study developed an enantioselective ligand-controlled rhodium(I)-catalyzed cycloisomerization of 1,6-allenynes for the synthesis of 5/6-fused bicyclic[4.3.0]nonadene skeletons through a 5-exo-dig cyclization pathway. Notably, this synthetic method also works for cyclic 1,6-allenynes to afford the diasteroselective construction of tricyclic products, which are challenging to synthesize using classical methods. The rate-determining step involving the C-H bond activation is highly regioselective and stereoconvergent, which was attained by the screening of ligands, solvents and additives. Further studies on the application of this method to the synthesis of natural products are in progress.

Methods

Procedures for synthesis of 2 and 5. In an oven-dried Schlenk tube, [Rh(CH3)2Cl]2 (0.005 mmol) and the chiral diphosphane ligand (0.01 mmol) were dissolved in freshly distilled 1,4-dioxane (1.0 mL). The mixture was stirred at 25 °C under argon for 0.5 h. Then AgI (0.01 mmol) was added to the solution and was stirred at 25 °C for additional 6 h. Then AgI (0.02 mmol) was added to the mixture and was stirred for further 15 min, followed by adding 1,4-dioxane (3 mL) and the 1,6-allenylene 1 or 4 (0.01 mmol) successively. The resulting mixture was stirred at 40 °C under argon until no starting material was detected by TLC. Upon the completion of the reaction, the solvent was removed. The crude mixture was directly subjected to column Chromatography on silica gel using petrol ether/EtOAc (30:1–10:1) as eluent to give the desired product.

Procedures for synthesis of 3 and 6. In an oven-dried Schlenk tube, [Rh(CH3)2Cl]2 (0.0025 mmol) and (±)-BINAP (0.005 mmol) were dissolved in freshly distilled 1,4-dioxane (1.0 mL). The mixture was stirred at 25 °C under argon for 0.5 h. Then AgI salt (0.01 mmol) was added to the mixture and was stirred for further 15 min, followed by adding 1,4-dioxane (1 mL) and the 1,6-allenylene 1 or 4 (0.01 mmol) successively. The resulting mixture was stirred at 25 °C under argon until no starting material was detected by TLC. Upon the completion of the reaction, the solvent was removed. The crude mixture was directly subjected to column Chromatography on silica gel using petrol ether/EtOAc (30:1–10:1) as eluent to give the desired product.

Measurement of enantiomeric excess (ee). Racemic 5/6 bicyclic products were prepared with (±)-DTBM-BIPHEP as the chiral ligand according to the general procedure described above. Similarly, optically active 5/6 bicyclic products were prepared with (S)-DTBM-BIPHEP as the chiral ligand according to the procedure described above. The ee value was determined by chiral HPLC (CHIRALPAK AD-H, OD-H, AS-H and IB-H column).

Computational Details. All DFT calculations were performed using the Gaussian 09 program60,61, except for the single-point gas-phase calculations by PW6B95D3 method, which were performed by the Gaussian 16 program. M06-L method was also performed to examine the effect of the functionals on the energetic profiles. Moreover, single-point calculations in gas phase PW6B95D3 were also carried out.

Data availability

Crystallographic data for the structure 2g reported in this paper have been deposited at the Cambridge Crystallographic Data Centre under deposition number CCDC 1586680. Copies of the data can be obtained free of charge via www.ccdc.cam.ac.uk. All other data for supporting the findings of this study, including experimental procedures and compound characterization, are available within the paper and its Supplementary Information, or from the corresponding author upon reasonable request.

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Author contribution

X.D., L-Y.S., J.L. contributed equally to this work. H.L. and X.Z. directed the project. X.D., L-Y.S., H.L. and X.Z. contributed to the conception and design of the experiments. X.D., L-Y.S. and Y-Q.G. performed the experiments and analyzed the data. J.L. and X.Z. carried out the computations. X.D., L-Y.S. and J.L. wrote the manuscript with feedback and guidance from L. W.C., H.L. and X.Z. All authors discussed the experimental results and commented on the manuscript.
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