Copper-Catalyzed Enantioselective Coupling between Allylboronates and Phosphates with a Phenol-Carbene Chiral Ligand: Asymmetric Synthesis of Chiral Branched 1,5-Dienes

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Abstract
This report presents details of the Cu-catalyzed enantioselective allyl–allyl coupling reaction between allylboronates and (Z)-allylic phosphates using a new chiral N-heterocyclic carbene (NHC) ligand containing a phenolic hydroxyl group. The copper catalysis delivered enantioenriched chiral 1,5-dienes with a tertiary stereogenic center. Various functional group compatibility and the use of earth-abundant and relatively low-toxicity Cu as a metal were attractive features of this protocol. The utility of the chiral phenol-NHC ligand for enantioselective copper catalysis with organoboron compounds was demonstrated. Enantio-discrimination models were discussed.

Key words: asymmetric catalysis · allylic substitution · synthetic method · copper catalysis · organoboron

INTRODUCTION AND BACKGROUND
Chiral 1,5-dienes with a stereogenic center at the allylic/homoallylic position are found in many important biologically active molecules such as FK-506, Plakortide E, and Chaetoglobosin A (Figure 1) [1], and also serve as useful building blocks in organic synthesis due to the versatility of the two alkene functionalities for further transformations. While several methods have been developed to produce chiral 1,5-dienes[2], enantioselective γ-substitution of allyl alcohol derivatives with organometal reagents (allyl–allyl) using the chiral transition metal complexes as catalysts is the most straightforward because it uses readily available substrates.[3]

In 2010, Morken and co-workers reported the pioneering example of catalytic asymmetric allyl–allyl coupling; Pd-catalyzed allyl–allyl coupling between substituted allylboronates[4] and (E)-allylic carbonates occurred with high regio- and enantioselectivity.[5] This protocol enabled access to chiral 1,5-dienes containing contiguous stereogenic centers with high diastereo- and enantioselectivity. More recently, Feringa's group reported asymmetric cross-coupling between allyl Grignard reagents and (E)-allyl bromides using the copper-chiral monodentate phosphoramidite catalyst, but only moderate SN2' regioselectivity was obtained.[6] In 2014, Carreira et al. developed Ir-catalyzed regio- and enantioselective allylic cross-coupling between allylsilanes and secondary aromatic allylic alcohols.[7] Despite these efforts, the allyl–allyl coupling was limited to use of acyclic (E)-allylic electrophiles.

Recently, the Cu-catalyzed enantioselective allyl–allyl coupling between allylboronates and allylic phosphates[8-11] using a new chiral N-heterocyclic carbene (NHC) ligand bearing a phenolic hydroxyl group[12,13] was reported. Reaction occurred with exceptional γ-regioselectivity and high enantioselectivity. Various functional groups were tolerated. The ability to use (Z)-aliphatic allylic substrates in the copper catalysis was complementary to Morken's Pd system (in their reports, only primary (E)-allylic electrophiles were used).[5] The present report describes the details of further studies of this Cu-catalyzed enantioselective allyl–allyl coupling.[8]

RESULTS AND DISCUSSION
Optimization. Enantioselective SnZ' allylic alkylation between non-allylic allylboranes (allyl-9-BBN) and primary allylic substrates using a catalytic amount of a chiral bisphosphine/Cu(I) complex and a stoichiometric amount of potassium alkoxide base has been reported.[14] The results prompted the initiation of a program to develop a Cu-catalyzed enantioselective allylic substitution with allylboron reagents.
For screening of the reaction conditions, commercially available allylboronic acid pinacol esters were used instead of the allyl-1-9-BBN reagents (Table 1). While investigating an effective achiral ligand that could selectively produce the racemic, branched γ-substitution product (3aa), a ring-saturated NHC/Cu complex prepared in situ from 1,3-bis(2,4,6-trimethylphenyl)imidazolidin chloride (SIMes·HCl), CuCl, and KOMe was produced in high yield (93%) with exclusive γ-regioselectivity (γ/α > 99:1) to form the branched coupling product 3aa from reaction between 2-allyl-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (1a) and γ-monosubstituted primary (Z)-allylic phosphate 2a in THF at –20 °C (entry 1). In contrast to the excellent performance of the ring-saturated NHC ligand SIMes, the corresponding unsaturated NHC ligand IMes derived from 1,3-bis(2,4,6-trimethylphenyl)imidazolidin chloride (IMes·HCl), gave a mixture of branched and linear products with a low γ-regioselectivity (62:38) and moderate total product yield (entry 2). Without a ligand, or with 1,10-phenanthroline (Phen) or 1,2-bis(diphenylphosphino)ethane (DPPE) ligands, no reaction occurred (entries 3–5). The use of triphenylphosphine (Ph3P) as a monodentate phosphine ligand gave only the linear substitution product (99:1) (entry 11). Furthermore, the enantioselectivity was increased (99% ee) by decreasing the reaction temperature to –99 °C (entry 12). In contrast, the naphthol-NHC chiral ligands L5 were not effective (entries 13 and 14).

Table 1. Ligand effects for reaction between 1a and (Z)-2a

<table>
<thead>
<tr>
<th>Entry</th>
<th>Ligand</th>
<th>Temp (°C)</th>
<th>Yield (%)</th>
<th>γ/α</th>
<th>ee (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Simes·HCl</td>
<td>–20</td>
<td>99</td>
<td>&gt;99:1</td>
<td>–</td>
</tr>
<tr>
<td>2</td>
<td>IMes·HCl</td>
<td>–20</td>
<td>65</td>
<td>62:38</td>
<td>–</td>
</tr>
<tr>
<td>3</td>
<td>Phen</td>
<td>–20</td>
<td>0</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>4</td>
<td>DPPE</td>
<td>–20</td>
<td>0</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Next, the effect of copper salts (Table 2) was investigated. When CuOAc was used as the catalyst, regioselectivity (γ/α, 91:9) and enantioselectivity (76% ee) decreased. The use of CuOAc, instead of Cu(I) salt, resulted in a modest yield and low selectivities. Changing CuCl to CuOTf afforded similar selectivity but a lower product yield. Use of MesCu and cationic Cu(MeCN)PF6 was as effective as CuCl, and gave comparable results.

The effect of solvent is shown in Table 2. Reaction with toluene gave only the racemic product in moderate yield (43%) and low regioselectivity (γ/α 64:36). Dichloromethane was ineffective in the reaction (26% yield, γ/α 71:29, 51% ee). No reaction occurred in MeCN or hexane.

Table 2. Effects of copper salts and solvents

<table>
<thead>
<tr>
<th>Entry</th>
<th>Cu Salt</th>
<th>Solvent</th>
<th>Yield (%)</th>
<th>γ/α</th>
<th>ee (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CuCl</td>
<td>THF</td>
<td>83</td>
<td>&gt;99:1</td>
<td>92</td>
</tr>
<tr>
<td>2</td>
<td>CuOAc</td>
<td>THF</td>
<td>85</td>
<td>91:7</td>
<td>76</td>
</tr>
<tr>
<td>3</td>
<td>Cu(OAc)2</td>
<td>THF</td>
<td>68</td>
<td>73:27</td>
<td>52</td>
</tr>
<tr>
<td>4</td>
<td>CuOTf</td>
<td>THF</td>
<td>48</td>
<td>&gt;99:1</td>
<td>90</td>
</tr>
<tr>
<td>5</td>
<td>MesCu</td>
<td>THF</td>
<td>85</td>
<td>&gt;99:1</td>
<td>89</td>
</tr>
<tr>
<td>6</td>
<td>Cu(MeCN)PF6</td>
<td>THF</td>
<td>73</td>
<td>&gt;99:1</td>
<td>88</td>
</tr>
<tr>
<td>7</td>
<td>CuCl</td>
<td>toluene</td>
<td>43</td>
<td>64:36</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>CuCl</td>
<td>DCM</td>
<td>26</td>
<td>72:29</td>
<td>51</td>
</tr>
<tr>
<td>9</td>
<td>MeCN</td>
<td>0</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
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<td>10</td>
<td>CuCl</td>
<td>hexane</td>
<td>0</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

[a] Data are taken from ref 8; Conditions: 1a (0.24 mmol), (Z)-2a (0.15 mmol), CuCl/ligand (10 mol%), KOMe (0.18 mmol), THF (0.6 mL) for 20 h. [b] Yield of isolated product. [c] Determined by H NMR analysis of the crude product. [d] The ee was determined by HPLC. [e] Condition: 1a (1.9 mmol) and (Z)-2a (1.2 mmol) were used. Reaction was conducted for 48 h.
solubility of LiCl or LiOP(O)(OEt)_2, which may form inactive Cu species through ionic interactions. (entry 5). The structure of the alkoxide moiety of the base also had a strong impact on yield, regioselectivity, and enantioselectivity. Thus, when KOMe was changed to a sterically more demanding base, KOtBu product yield was moderate and both regioselectivity and enantioselectivity decreased significantly (entry 6). This result suggests that the trialkyboron ROBpin may participate in the reaction because Lewis acids activate the phosphate leaving group (see Figure 4). Coupling reaction with KCO_3 did not occur (entry 7).

**Table 3. Effect of leaving group and base[a]**

<table>
<thead>
<tr>
<th>Entry</th>
<th>Leaving group</th>
<th>Base</th>
<th>Yield (%)</th>
<th>(β:α)-3aa</th>
<th>(β:α)-4aa</th>
<th>ee (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>OP(O)(OEt)_2 (2a)</td>
<td>KOME</td>
<td>83</td>
<td>&gt;99:1</td>
<td>92</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Cl</td>
<td>KOME</td>
<td>89</td>
<td>94:6</td>
<td>64</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Br</td>
<td>KOME</td>
<td>85</td>
<td>82:18</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>OP(O)(OEt)_2 (2a)</td>
<td>NaOMe</td>
<td>91</td>
<td>89:11</td>
<td>74</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>OP(O)(OEt)_2 (2a)</td>
<td>LiOMe</td>
<td>0</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>OP(O)(OEt)_2 (2a)</td>
<td>KODBu</td>
<td>67</td>
<td>82:18</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>OP(O)(OEt)_2 (2a)</td>
<td>KCO_3</td>
<td>0</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
</tbody>
</table>

[a] Data are taken from ref 8 for entries 1–12 and 15–17. Conditions: 1a (0.24 mmol), (β:α)-2 (0.15 mmol), CuCl/(S,S)-L5-HBF_4 (10 mol%), base (0.18 mmol), THF (0.6 mL), –20 °C for 20 h. [b] Yield of isolated product. [c] Determined by 1H NMR of crude product. [d] The ee was determined by HPLC.

**Substrate Scopes.** (2)-Allylic phosphates with various aliphatic substituents were reacted with 1a in the Cu-L5 catalyst system (Table 4). When the 2-phenylethyl group of 2a was replaced with a benzyl or octyl group, coupling proceeded with excellent γ-selectivity and preservation of enantioselectivity (entries 1 and 3). A sterically more demanding γ-substituent, such as a cyclohexyl group, was also tolerated and produced a high level of enantioselectivity (80% ee) (entry 4).[17] Notably, the enantioselective reaction with 2-buten-1,4-diol derivatives, which have two potential leaving groups at different allylic positions, occurred with the allylic C-O bonds in the ether or carboxylic ester leaving groups untouched (entries 5–12 and 15).

The reaction has a great functional group compatibility (entries 2 and 5–12, 15–17). For example, an allylic phosphate (2) bearing a 1,3-benzodioxole (2c), THP ether (2f), benzyl ether (2g), allyl ether (2h), q,[17] pivalate (2i), carbamate (2p) or p-toluenesulfonate (2r) group as the aliphatic γ-substituent, reacted with 1a to produce the corresponding 1,5-diene derivatives in good yields with high enantioselectivities (85–97% ee) (entries 2, 5–8, 15–17). Methoxy, trifluoromethyl, bromo, or dimethylamino substituents were tolerated in the aromatic ring of the benzoate groups (entries 9–12). However, no reaction occurred with the allylic phosphate bearing a nitro (2n) or cyano (2o) group (entries 13 and 14).

The potential for scaling up the enantioselective allyl–allyl coupling was examined on a preparative scale (Eq. 1). Reaction between allylboronate 1a (9.4 mmol, 1.5 g) and allylic phosphate 2h (5.9 mmol, 2.0 g) afforded only the branched coupling product in 73% yield (0.98 g, 4.3 mmol) with 92% ee.

**Table 4. Scope of allylic phosphates[a]**

<table>
<thead>
<tr>
<th>Entry</th>
<th>Phosphate</th>
<th>Product</th>
<th>Temp (°C)</th>
<th>Yield (%)</th>
<th>ee (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2b</td>
<td>3ab</td>
<td>–50</td>
<td>62</td>
<td>86</td>
</tr>
<tr>
<td>2</td>
<td>2c</td>
<td>3ac</td>
<td>–30</td>
<td>97</td>
<td>86</td>
</tr>
<tr>
<td>3</td>
<td>2d</td>
<td>3ad</td>
<td>–40</td>
<td>85</td>
<td>84</td>
</tr>
<tr>
<td>4</td>
<td>2e</td>
<td>3ae</td>
<td>–50</td>
<td>59</td>
<td>80</td>
</tr>
<tr>
<td>5</td>
<td>3af</td>
<td>3af-al</td>
<td>–30</td>
<td>83</td>
<td>90</td>
</tr>
<tr>
<td>6</td>
<td>3ag</td>
<td>3ag</td>
<td>–50</td>
<td>75</td>
<td>85</td>
</tr>
<tr>
<td>7</td>
<td>3ah</td>
<td>3ah</td>
<td>–50</td>
<td>78</td>
<td>97</td>
</tr>
<tr>
<td>8</td>
<td>3ai</td>
<td>3ai</td>
<td>–30</td>
<td>70</td>
<td>91</td>
</tr>
</tbody>
</table>

[a] Data are taken from ref 8 for entries 1–12 and 15–17. Conditions: 1a (0.24 mmol), (β:α)-2 (0.15 mmol), CuCl/(S,S)-L5-HBF_4 (10 mol%), KOMe (0.18 mmol), THF (0.6 mL) for 48 h. [b] Yield of isolated product. [c] Constitutional isomer ratio γ/α > 20:1 (determined by 1H NMR of crude product). [d] The ee was determined by HPLC.

The copper-catalyzed allyl-allyl coupling reaction between 1a and enantioenriched 2-buten-1,4-diol derivative (S)-2s (99% ee) with (R,R)-L5·HBF_4 (i.e., an enantiomeric isomer of (S,S)-L5·HBF_4) gave the corresponding 1,5-diene 3as with two adjacent stereogenic centers with a 2S,3S-configuration in modest yield (51%) and high diastereoselectivity (d.r. 90:10) (Eq. 2). Without a ligand, or with (S,S)-L5·HBF_4, the reaction gave no or only a trace of the coupling product. Thus, the use of L5 is mandatory, and (R,R)-L5-Cu system and the (S)-2s substrate is a matched pair, while (S,S)-L5/Cu complex and (S)-2s is mismatched. This result is in accord with a consideration of the Felkin-Anh model as depicted in Figure 2, which predicts preferred approach of organocopper nucleophile to Si-face of the allylic plain with a minimum A1,L3-strain.
Reactions of β-substituted allylboronate derivatives using the Cu-L5 catalyst system were investigated (Table 5). Methallylboronate 1b and 2-ethyl-2-propen-1-ylboronate 1c reacted with (Z)-2a with excellent γ-selectivity (95% and 80% ee, respectively) (entries 1 and 2). An allylboronate with a hexyl, benzyl, or phenyl group at the β-position (1d–f) underwent reaction to afford the coupling products with enantiomeric excesses greater than 80%, while the regioselectivities were moderate (entries 3–5). The allylboronate with a chloro group at the β-position did not react (entry 6). In addition, no reaction occurred with γ-substituted allylboronates such as trans- or cis-crotylboronates.

**Table 5. Scope of allylboronates[6]**

<table>
<thead>
<tr>
<th>Entry</th>
<th>Allylboronate</th>
<th>Phosphate</th>
<th>Product</th>
<th>Yield (%)</th>
<th>γ/α (%)</th>
<th>Ee (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1b PPh</td>
<td>OP = OP(O)(OEt)2</td>
<td>2a</td>
<td>77</td>
<td>20:1</td>
<td>95</td>
</tr>
<tr>
<td>2</td>
<td>1c PPh</td>
<td>OP = OP(O)(OEt)2</td>
<td>2a</td>
<td>50</td>
<td>20:1</td>
<td>80</td>
</tr>
<tr>
<td>3</td>
<td>1d PPh</td>
<td>OP = OP(O)(OEt)2</td>
<td>3a</td>
<td>87</td>
<td>84:16</td>
<td>80</td>
</tr>
<tr>
<td>4</td>
<td>1e PPh</td>
<td>OP = OP(O)(OEt)2</td>
<td>3a</td>
<td>59</td>
<td>87:13</td>
<td>82</td>
</tr>
<tr>
<td>5</td>
<td>1f PPh</td>
<td>OP = OP(O)(OEt)2</td>
<td>3a</td>
<td>89</td>
<td>78:22</td>
<td>83</td>
</tr>
<tr>
<td>6</td>
<td>1g PPh</td>
<td>OP = OP(O)(OEt)2</td>
<td>3g</td>
<td>0</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

[a] Data are taken from ref 8 for entries 1–5. Conditions: 1 (0.24 mmol), (Z)-2 (0.15 mmol), CuCl/L5-HBF4 (10 mol %), KOMe (0.18 mmol), THF (0.6 mL), –50 °C (entry 1) or –30 °C (entries 2–6) for 48 h. [b] Yield of isolated product. [c] Determined by 1H NMR of crude product. [d] The ee was determined by HPLC.

The coupling reaction between 1a and cis-4-cyclopentene-1,3-diol diphosphate 2a catalyzed by the Cu-L5 system occurred with adequate enantioselectivity, giving the trans-1,2-isomer 3au [Eq. 3][17,19]. Reaction with cis-4-cyclohexene-1,3-diol derivative 2v gave the trans-1,2-isomer 3av with moderate enantiocontrol (66% ee) [Eq. 4]. These stereochemical results indicate that the present Cu-catalyzed reaction proceeded through an anti-SN2′ type reaction pathway. Morken’s Pd-catalyzed protocol has not been applied to this type of cyclic allylic electrophile involving a Z alkene moiety. [3]

**Mechanistic Study and Proposed Reaction Pathway.** The alkene geometry of the allylic phosphates influenced both regio- and enantioselectivity. Thus, reaction between 1a and (E)-2a under the conditions described in Table 1, entry 11 gave the linear α-substitution product (E)-4aa preferentially with minor formation of (S)-3aa (71% ee), the antipode of the product derived from (Z)-2a (Eq. 5).[18] This α-selectivity appeared to occur via allylic 1,3-migration of Cu in the allylcopper(III) species. To gain insight into the nature of the postulated allylcopper(III) species, secondary allylic phosphate 2a', a constitutional isomer of (Z)-2a, was reacted under the same conditions [Eq. 6].[19] Interestingly, this reaction gave results similar to reaction with (E)-2a. The convergence observed in the regioselectivity and stereochemistry suggests that (E)-2a and 2a' led to a common equilibrium mixture of the allylcopper(III) species prior to reductive elimination to form the product mixture (Figure 3).

Based on the assumption that γ-selective reaction of (Z)-2 also occurs via allylcopper(III) intermediates, a catalytic cycle was proposed for the enantioselective allyl-allyl coupling catalyzed by the Cu-L5 system, as shown in Figure 4.[20] An allylcopper(II) complex (A) was formed from reaction between CuCl, L5-HBF4, and KOMe. For this complex, the chiral NHC ligand coordinated to Cu as an anionic C,O-bidentate ligand. Then, transmetallation between A and an allylborate (B) [21] afforded the potassium phenoxo(allyl)cuprate (C). Compound C formed a π-complex (D) with the allylic phosphate 2a, in which the Cu was anti to the phosphate leaving group. The MeOBpin may activate the phosphate group as a Lewis acid.[14d] Subsequently, oxidative addition produced (π-en-σ-yl)copper(III) complex E1 with a secondary sp2-carbon atom bound to Cu. Facile reductive elimination of E1, which was faster than allylic 1,3-Cu-migration to form E2, produced the
branched γ-substitution product 3 and regenerated alkoxy copper(I) complex A (Figs. 5 and 6 for enantio- discrimination models).

Thus, the crucial dependence of regioselectivity on the E/Z geometry of the allylic substrate (Z) can be explained by the greater instability of the allylcopper(III) intermediate E2 compared to the corresponding Cu(III) species (E1) produced from the E substrate, due to larger steric repulsion in the allyl moiety derived from the Z substrate (Fig. 3). Similar consideration may be applicable to the corresponding transition states that determine the E/Z-isomeric product distribution.

Reactions of E- and Z-isomers of 2a gave the antipodes of 3aa, (Table 1, entry 11 vs. Eq. 5), and the products from (Z)-2a were produced with greater enantioselectivity. This led to the proposal of the enantioselection models shown in Figs. 5 and 6. In the π-complex D (Fig. 4), the chiral copper center adopted a tetrahedral coordination geometry including the C,O-bidentate chelation. The K+ ion bridged the phenoxide oxygen and MeO-Bpin, which interacted with the phosphate leaving group as a Lewis acid. These assumptions suggest four possible π-complexes (D1 and D2 for the major enantiomer; D3 and D4 for the minor enantiomer) (Fig. 5). Complex D1 is the most favorable, because it results in the fewest steric repulsions between catalyst and allylic phosphate. Complexes D2, D3, and D4 appear to be destabilized by the steric repulsions between the γ-substituent (R) and nonhydroxylated N-aryl group or one of the phenyl groups on the imidazolidine ring. These conclusions are consistent with the experimental observations that the enantioselectivity is influenced by the steric nature of the γ-substituent (R) (Table 4, entries 3 and 4) or the nonhydroxylated N-aryl group in the phenolic NHC ligands (Table 1, entries 10 and 11).

CONCLUSIONS

In conclusion, a versatile method was developed for Cu-catalyzed enantioselective allyl-allyl coupling between allylboronates and (Z)-acyclic and cyclic allylic phosphates to form various chiral 1,5-diene derivatives. Catalysis of a Cu(I) complex with a new phenol-NHC chiral ligand enabled the reaction, demonstrating the utility of this class of chiral ligands for enantioselective copper catalysis with organoboron compounds. This Cu-catalyzed protocol provides efficient access to functionalized, enanto-enriched chiral 1,5-dienes with a stereogenic carbon center at the allylic/homoallylic position. The broad functional group compatibility and the use of earth-abundant and relatively low-toxic Cu as a metal are attractive features of this protocol. A functional role for the phenolic
hydroxy group in the chiral NHC ligand was suggested by the results.

EXPERIMENTAL SECTION

Instrumentation and Chemicals

NMR spectra were recorded on a JEOL ECS-400, operating at 400 MHz for 1H NMR, 100.5 MHz for 13C NMR and 128 MHz for 19F NMR. Chemical shift values for 1H and 13C are referenced to Me-Si and the residual solvent resonances, respectively. Chemical shifts are reported in δ ppm. Mass spectra were obtained with Thermo Fisher Scientific Exactive, JEOL JMS-T100LP or JEOL JMS-700TG at the Instrumental Analysis Division, Global Facility Center, Creative Research Institute, Hokkaido University. HPLC analyses were conducted on a HITACHI ELITE LaChrom system with a HITACHI L-2455 diode array detector or a HITACHI L-2455 diode array detector. Optical rotations were measured on a JASCO P-2200. TLC analyses were performed on commercial glass plates bearing 0.25-mm layer of Merck Silica gel 60F254. A solution of propargylic alcohol (1.1 g, 5 mmol) in hexane (4.3 mL)/acetone (790 μL) was added to the mixture of Pd/CaCO3 (40.0 mg) and quinoline (397 μL, 3.6 mmol), and then the reaction mixture was filled with hydrogen gas. After confirming the completion of the reaction by 1H NMR, Pd/CaCO3 was removed by filtration, and the resulting solution was evaporated under reduced pressure. The residue was purified by flash chromatography on silica gel (0–10% EtOAc/hexane) to give (S,Z)-4-[(tert-butyldimethylsilyl)oxy]-2-penten-1-ol in 80% yield (874 mg, 40 mmol). To a solution of (S,Z)-4-[(tert-butyldimethylsilyl)oxy]-2-penten-1-ol (874 mg, 4.0 mmol) in pyridine (6.1 mL), EtOAc (679 μL, 4.8 mmol) and DMAP (24 mg, 0.2 mmol) were sequentially added at 0 °C. After being stirred at rt for 3 h, the reaction mixture was diluted with EtOAc (20 mL) and was treated with H2O (2 mL). The resulting mixture was washed with saturated CuSO4 aq. (10 mL × 3) and brine, dried over anhydrous MgSO4, filtered, and evaporated under reduced pressure. The residue was purified through flash column chromatography on silica gel (10–45% EtOAc/hexane) to provide (S)-2a-[(tert-butyldimethylsilyl)oxy]-2-penten-1-yl diethyl phosphate (2s) in 94% yield (1.3 g, 3.8 mmol). The ee value of (S)-2s (99% ee) was determined by chiral HPLC analysis of the p-Om-azoeto derivative of (S)-2a-[(tert-butyldimethylsilyl)oxy]-2-penten-1-yl diethyl phosphate (2s) (100 MHz, CDCl3, 1.0 mL × 250 mm, Daicel Chemical Industries, hexane/2-propanol 99:1, 0.5 mL/min, 40°C, 220 nm UV detector; retention time = 13.7 min, for R isomer and 17.7 min for S isomer).

Characterization Data for Allylic Phosphate

(S,Z)-4-[(tert-Butyldimethylsilyl)oxy]-2-penten-1-yl diethyl phosphate (2s) (99% ee)

Colorless Oil. IR (neat) 667, 775, 830, 975, 1026, 1254, 1369, 1393, 1473, 2858, 2930, 2957cm–1. 1H NMR (400 MHz, CDCl3) δ 0.04 (s, 3H), 0.06 (s, 3H), 0.89 (s, 9H), 1.20 (d, J = 6.4 Hz, 3H), 1.34 (t, J = 7.2 Hz, 6H), 4.11 (quintet, J = 7.2 Hz, 4H), 4.55–4.69 (m, 3H), 5.48 (dt, J = 11.2, 6.0 Hz, 1H), 5.64 (dd, J = 11.2, 8.0 Hz, 1H). 13C NMR (100 MHz, CDCl3) δ –4.8, –4.6, 16.1 (d, J = 6.7Hz), 18.1, 24.6, 25.7, 63.0 (d, J = 4.8 Hz), 63.7 (d, J = 5.7 Hz), 65.1, 122.3 (d, J = 6.6 Hz), 139.2. HRMS–ESI (m/z) for C29H43O5NaPSi 375.1727 (99% ee) was determined.

Preparation of Allylic Phosphate (5)-2s

Colorless Oil. IR (neat) 667, 775, 830, 975, 1026, 1254, 1369, 1393, 1473, 2858, 2930, 2957cm–1. 1H NMR (400 MHz, CDCl3) δ 0.04 (s, 3H), 0.06 (s, 3H), 0.89 (s, 9H), 1.20 (d, J = 6.4 Hz, 3H), 1.34 (t, J = 7.2 Hz, 6H), 4.11 (quintet, J = 7.2 Hz, 4H), 4.55–4.69 (m, 3H), 5.48 (dt, J = 11.2, 6.0 Hz, 1H), 5.64 (dd, J = 11.2, 8.0 Hz, 1H). 13C NMR (100 MHz, CDCl3) δ –4.8, –4.6, 16.1 (d, J = 6.7Hz), 18.1, 24.6, 25.7, 63.0 (d, J = 4.8 Hz), 63.7 (d, J = 5.7 Hz), 65.1, 122.3 (d, J = 6.6 Hz), 139.2. HRMS–ESI (m/z) for C29H43O5NaPSi 375.1727; found, 375.1722. [α]D25 +150 (c 1.17, CHCl3).
The product 3ac was purified by flash chromatography on silica gel (5% EtOAc/hexane) (31.5 mg, 0.14 mmol, 97% isolated yield from 2c).

(R)-4-Vinyl-1-dodecene (3ad)
The product 3ad was purified by flash chromatography on silica gel (hexane) (24.7 mg, 0.12 mmol, 85% isolated yield from 2d).

(R)-Hexa-1,5-dien-3-ylcyclohexane (3ae)
The product 3ae was purified by flash chromatography on silica gel (pentane) (14.6 mg, 0.09 mmol, 59% isolated yield from 2e).

(R)-2-[[2-Vinyl-4-penten-1-yl]oxy]tetrahydro-2H-pyran (3af)
(Diastereomeric ratio 1:1)
The product 3af was purified by flash chromatography on silica gel (0–2% EtOAc/hexane) (24.3 mg, 0.12 mmol, 83% isolated yield from 2f).

(R)-[(2-Vinyl-4-penten-1-yl)oxy]methyl)benzene (3ag)
The product 3ag was purified by flash chromatography on silica gel (0–1% EtOAc/hexane) (22.8 mg, 0.11 mmol, 75% isolated yield from 2g).

(R)-tert-Butyldimethyl(2-vinylpent-4-en-1-yl)oxy)silane (3ah)
The product 3ah was purified by flash chromatography on silica gel (0–1% EtOAc/hexane) (26.6 mg, 0.12 mmol, 79% isolated yield from 2h).

(R)-2-Vinyl-4-penten-1-yl Pivalate (3ai)
The product 3ai was purified by flash chromatography on silica gel (0–2% EtOAc/hexane) (20.6 mg, 0.11 mmol, 70% isolated yield from 2i).

(R)-2-Vinyl-4-penten-1-yl 4-Methoxybenzoate (3aj)
The product 3aj was purified by flash chromatography on silica gel (0–2% EtOAc/hexane) (31.2 mg, 0.13 mmol, 85% isolated yield from 2j).

(R)-2-Vinyl-4-penten-1-yl 4-(Trifluoromethyl)benzoate (3ak)
The product 3ak was purified by flash chromatography on silica gel (0–2% EtOAc/hexane) (25.9 mg, 0.09 mmol, 61% isolated yield from 2k).

(R)-2-Vinyl-4-penten-1-yl 4-Bromobenzoate (3al)
The product 3al was purified by flash chromatography on silica gel (0–2% EtOAc/hexane) (28.8 mg, 0.10 mmol, 65% isolated yield from 2l).

(R)-2-Vinyl-4-penten-1-yl 4-(Dimethylamino)benzoate (3am)
The product 3am was purified by flash chromatography on silica gel (0–5% EtOAc/hexane) (34.0 mg, 0.13 mmol, 87% isolated yield from 2m).

(R)-1-Benzyl 4-[(2-Vinyl-4-penten-1-yl)piperidine-1,4-dicarboxylate (3ap)
The product 3ap was purified by flash chromatography on silica gel (5–10% EtOAc/hexane) (43.0 mg, 0.12 mmol, 80% isolated yield from 2p).

(R)-tert-Butyldimethyl(4-vinyl-6-hepten-1-yl)oxy)silane (3aq)
The product 3aq was purified by flash chromatography on silica gel (0–1% EtOAc/hexane) (29.8 mg, 0.12 mmol, 78% isolated yield from 2q).

(R)-4-Vinyl-6-hepten-1-yl 4-Methylbenzenesulphonate (3ar)
The product 3ar was purified by flash chromatography on silica gel (0–5% EtOAc/hexane) (38.7 mg, 0.13 mmol, 88% isolated yield from 2r).

tert-Butyldimethyl(25,35)-3-vinyl-5-hexen-2-yl)oxy)silane (3as)
The product 3as was purified by flash chromatography on silica gel (0–2% EtOAc/hexane) (22.2 mg, 0.09 mmol, 61% isolated yield from 2s).

Colorless Oil, IR (neat) 664, 772, 830, 910, 994, 1072, 1254, 1361, 1374, 1463, 1472, 1641, 2858, 2887, 2930, 2957, 3078 cm\(^{-1}\). \(\text{H}^1\ NMR (400 MHz, CDCl}_3)\): 6.05 (s, 6H), 0.89 (s, 9H), 1.08 (d, \(J = 6.4\) Hz, 3H), 1.98–2.12 (m, 2H), 2.34 (m, 1H), 3.70 (quintet, \(J = 6.4\) Hz, 1H), 4.95–5.08 (m, 4H), 5.59–5.88 (m, 2H). \(\text{C}^1\) NMR (100 MHz, CDCl\(_3\)): 8 = 4.8, 4.3, 17.9, 20.8, 25.7, 34.5, 51.7, 70.5, 115.2, 137.4, 139.1. HRMS –APCI (m/z): [M+H]\(^{+}\) calcd for C\(_{24}\)H\(_{38}\)OSi, 461.2682; found, 461.2682. \(\delta_{	ext{calc}}^0\) = +34 (c 0.37, CHCl\(_3\)). The d.r. (90:10) was determined by \(\text{H}^1\) NMR analysis of the crude product. The absolute configuration of 3as was assigned by consideration of the stereochemical pathway.

(R)-[5-Methyl-3-vinyl-5-hexen-1-yl]benzene (3ba)
The product 3ba was purified by flash chromatography on silica gel (hexane) (23.1 mg, 0.12 mmol, 77% isolated yield from (Z)-2a).

(R)-[5-Methylene-3-vinylheptyl]benzene (3ca)
The product 3ca was purified by flash chromatography on silica gel (hexane) (16.1 mg, 0.07 mmol, 50% isolated yield from (Z)-2a).

(R)-[5-Methylene-3-vinylundecyl]benzene (3da)
The product 3da was purified by flash chromatography on silica gel (hexane) (35.3 mg, 0.13 mmol, 87% isolated yield from (Z)-2a).

(R)-[2-Vinyl-4-hexenylhexane-1,6-diyl]dibenzene (3ea)
The product 3ea was purified by flash chromatography on silica gel (0–1% EtOAc/hexane) (24.7 mg, 0.08 mmol, 59% isolated yield from (Z)-2a).

(R)-[4-Methyl-1,5-hexadien-2-yl]benzene (3fa)
The product 3ft was purified by flash chromatography on silica gel (hexane) (23.0 mg, 0.13 mmol, 89% isolated yield from 2t). The isolated branched product (3Ot) was contaminated with a trace amount of the linear product.

(1R,2R)-2-Allyl-3-cyclopenten-1-yl Diethyl Phosphate (3au)
The product 3au was purified by flash chromatography on silica gel (20–50% EtOAc/hexane) (25.1 mg, 0.10 mmol, 64% isolated yield from 2u).

(1R,2R)-2-Allyl-3-cyclohexen-1-yl Diethyl Phosphate (3av)
The product 3av was purified by flash chromatography on silica gel (20–50% EtOAc/hexane) (21.3 mg, 0.08 mmol, 52% isolated yield from 2v).

Acknowledgment
This work was supported by Grants-in-Aid for Scientific Research (B) (No. 15H03803), JSPS, to H.O. and by CREST and ACT-C, JST, to M.S.

Supporting Information
Is there Supporting Information to be published? Click here to indicate YES or NO (text and links will be updated prior to publication).

References


The use of allyl-9-BBN reagent instead of 1a under the conditions for Table 1, entry 12 resulted in decreases in both enantioselectivity (87% ee) and product yield (30%) but with the exclusive regioselectivity (β/α>99:1) unchanged.


The absolute configurations of 3ae and 3ah were determined by comparison of the specific rotations with the values reported previously. See ref 5a. The absolute configuration of 3au was determined by the Mosher’s NMR spectroscopic method. Absolute configurations of the other products were assigned by consideration of the stereochemical pathway. See ref 8.

The linear α-substitution product was β-isomer.

Data are taken from ref 8 for Eq. 3–6.

Nakamura conducted DFT calculations on the mechanism of the reaction between [MeCu(CN)Li] and allyl acetate to form a square planar four-coordinate (σ-π-enyl)copper(III) species. [σ-π-enyl]copper(III) complex is determined at the oxidative addition step as a consequence of the asymmetric nature of MeCuCN. Our proposed mechanism is in accord with the Nakamura’s mechanism in which the (σ-π-enyl)copper(III) species is not in equilibrium with the corresponding (σ-π-enyl)coppor(III) species; the regioselectivity is determined at the oxidative addition step as a consequence of the asymmetric nature of MeCuCN. Our proposed mechanism is in accord with the Nakamura’s mechanism in that the reaction proceeds through oxidative addition of a cuprate to form the (σ-π-enyl)copper(III) species followed by reductive elimination. However, the coordination number of Ca in the allylkooper(III) complex is different by virtue of bidentate coordination of the anionic phenol-NHC chiral ligand (L). The strongly electron-donating NHC coordination should render the π-en coordination weaker, making the allylic 1,3-Cu-migration in the allylkooper(III) complex more feasible. See: a) Yoshikai, N.; Zhang, S.-L.; Nakamura, E. J. Am. Chem. Soc. 2008, 130, 12862. For the effect of a σ-donor ligand, see: b) Yamakawa, M.; Kato, S.; Nakamura, E. J. Am. Chem. Soc. 2004, 126, 6287.

Rapid formation of a tetraevatlon borate (B) was confirmed by 11B NMR spectroscopy. See ref 8.


**Biosketches**

<table>
<thead>
<tr>
<th>Photograph</th>
<th>Author</th>
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<tbody>
<tr>
<td><img src="image1.jpg" alt="Yuto Yasuda" /></td>
<td>Yuto Yasuda</td>
<td>Graduated from Hokkaido University in 2014. Received his M. Sc in 2016 from Hokkaido University under the supervision of Professor Masaya Sawamura. Currently, working on his Ph. D. thesis on development of copper-catalyzed asymmetric C–C bond formation reactions. JSPS research fellow (DC1) since 2016. Awards: CSJ Student Presentation Award (2014), CSJ Student Presentation Award (2016), Poster Award in 1st Singapore Japan Germany Trilateral Symposium on Precision Synthesis &amp; Catalysis (2017).</td>
</tr>
<tr>
<td><img src="image2.jpg" alt="Hirohisa Ohmiya" /></td>
<td>Hirohisa Ohmiya</td>
<td>Professor at Kanazawa University. Received his Ph. D. degree from Kyoto University in 2007 under the supervision of Professor Koichiro Oshima. Spent one year as a JSPS postdoctoral fellow in the group of Professor Timothy F. Jamison at Massachusetts Institute of Technology (USA). Worked with Professor Masaya Sawamura. Promoted to Associate Professor in 2010. Awards: Chemical Society of Japan Award for Young Scientists (2014) and the Young Scientist's Prize for the Commendation of Science and Technology by MEXT (2015).</td>
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<tr>
<td><img src="image3.jpg" alt="Masaya Sawamura" /></td>
<td>Masaya Sawamura</td>
<td>Professor at Hokkaido University. Received his Ph. D. degree from Kyoto University in 1989 under the supervision of Professor Yoshihiko Ito. Joined faculty of the same department as Assistant Professor. Spent one year as a researcher at Harvard University (Professor Stuart L. Schreiber, 1993–1994). Moved to Tokyo Institute of Technology and joined group of Professor Eiichi Nakamura as Assistant Professor. Promoted to Lecturer in 1996 and Associate Professor in 1997. Full Professor at Hokkaido University since 2001. Awards: Chemical Society of Japan Award for Young Scientists (1996), the Chemical Society of Japan Award for Creative Work (2012), the SSOCJ (The Society of Synthetic Organic Chemistry, Japan) Nissan Chemical Industries Award for Novel Reaction &amp; Method (2014), and the Nagoya Medal (Silver Medal, 2017).</td>
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