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Asymmetric Silaboration of Terminal Allenes Bearing α-Stereogenic Centers: Stereoselection Based on "Reagent Control"

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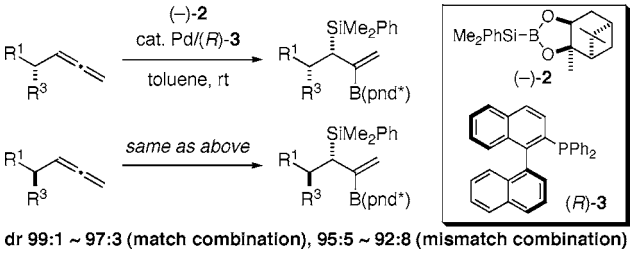
ABSTRACT



A highly enantioface-selective silaboration of allenes having stereogenic centers at the α-positions of the double bonds has been achieved using a combination of a chiral silylborane (–)-2 and a chiral Pd/(*R*)-3 catalyst. The chiral reagent system efficiently controlled the stereochemistry of the new stereogenic centers even in the reactions of mismatched combinations.

Transition-metal-catalyzed bismetalation of carbon−carbon unsaturated bonds is a powerful strategy for the preparation of compounds that contain multiple metallic elements.[1] In particular, bismetalation reactions that form chiral allylic metal species are expected to produce useful organometallic compounds for asymmetric C−C bond formations via an efficient chirality transfer.[2] Palladium-catalyzed silaboration of allenes is a highly efficient, established access to β-borylallylsilanes, which serve as unique allylation reagents, giving functionalized alkenylboron derivatives.[3,4] We have recently achieved the enantioface-selective silaboration of terminal allenes under double-asymmetric induction conditions using optically active silylborane (−)-**2** in the presence of a chiral ligand (*R*)-**3**[5] on palladium

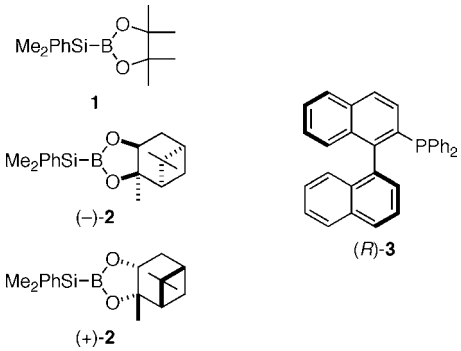


Figure 1. Silylboranes and ligand used for this study.

(Figure 1).[6] The silaboration gave enantioenriched β-borylallylsilanes with up to 96% de in the reactions of achiral terminal allenes.

(1) For selected reviews, see: (a) Beletskaya, I.; Moberg, C. *Chem. Rev.* **1999**, *99*, 3435. (b) Suginome, M.; Ito, Y. *Chem. Rev.* **2000**, *100*, 3221. (c) Ishiyama, T.; Miyaura, N. *J. Organomet. Chem.* **2000**, *611*, 392. (d) Suginome, M.; Ito, Y. *J. Organomet. Chem.* **2003**, *680*, 43. (e) Ishiyama, T.; Miyaura, N. *Chem. Rec.* **2004**, 3, 271. (f) Dembitsky, V. M.; Abu Ali, H.; Srebnik, M. *Adv. Organomet. Chem.* **2004**, *51*, 193.

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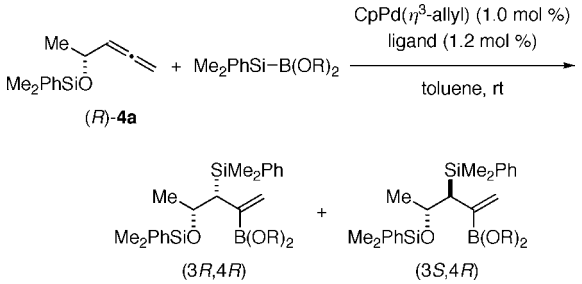
Our research interest then focused on the application of the enantioface-selective silaboration to α-chiral allene substrates, which would give diastereomeric *β*-borylallylsilanes. In general, the stereochemical course of the reactions of chiral substrates is affected by the existing stereochemistry.[7] This substrate-controlled stereoselection is more pronounced if the stereogenic centers exist in close proximity to the reaction centers. Via this route, a part of the possible diastereomers are not accessible. On the other hand, with another mode of stereocontrol, i.e., "reagent control", stereoselection is made solely by the stereochemical information contained within the chiral reagent(s). As the existing stereochemical information in the substrate has no influence on the stereoselection in the ideal reagent-controlled system, any enantiomerically pure diastereomer is accessible depending on the choice of chiral reagent. Such reagent-controlled stereoselective reactions are very important in the synthesis of complex organic molecules that have multiple stereogenic centers.[8] Herein, we disclose the "reagent-controlled" asymmetric silaboration of chiral terminal allenes that have an α-stereogenic center. A double-asymmetric induction system using a chiral silylborane and a chiral ligand was found to be highly effective in the synthesis of enantiopure diastereomers of *β*-borylallylsilanes.

(*R*)-4-Dimethylphenylsilyloxy-1,2-pentadiene ((*R*)-**4a**) was reacted with silylboranes **1** and **2** in the presence of 1.0 mol % of CpPd(η^3-allyl)[9] with 1.2 mol % of monodentate phosphine ligands (Table 1).[10,11] The reaction using achiral

Table 1. Silaboration of (*R*)-**4a**[a]



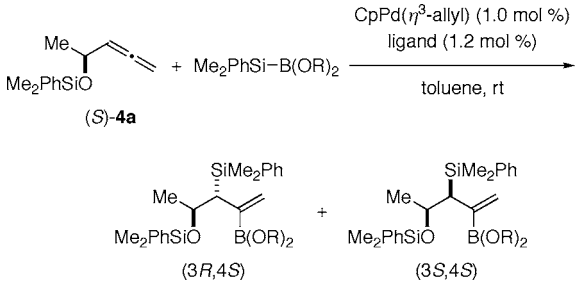
entry	silylborane	ligand	yield[b] (%)	(3*R*,4*R*)/(3*S*,4*R*)[c]
1	**1**	PPh_3	− (**5**)	67:33
2	**1**	(*R*)-**3**	98 (**5**)	89:11
3	(−)-**2**	PPh_3	95 (**6a**)	94:6
4	(−)-**2**	(*R*)-**3**	98 (**6a**)	98:2
5	(+)-**2**	(*R*)-**3**	(97)[d] (**6a′**)	73:27

[a] CpPd(η^3-allyl) (4.0 *μ*mol), ligand (4.8 *μ*mol), silylborane (0.40 mmol), and (*R*)-**4a** (0.48 mmol) were reacted in toluene (0.2 mL) at room temperature. [b] Isolated yield. [c] Determined by ^{1}H NMR. [d] A racemic mixture of **4a** was used for this entry. Isolated yield of a mixture of four diastereomers is shown.

silylborane **1** in the presence of a Pd/PPh_3 catalyst gave *β*-borylallylsilane **5** as the mixture of two diastereomers [(3*R*,4*R*)/(3*S*,4*R*) = 67:33, entry 1]. This result indicates that even a stereogenic center in close proximity to the reaction center did not affect the enantioface selectivity much, suggesting that this silaboration system is suitable for reagent-based stereocontrol. We then carried out the silaboration of (*R*)-**4a** using chiral reagent systems in which either the silylborane or the catalyst was chiral. The enantioface selectivity was considerably improved by the combined use of the achiral silylborane **1** and a chiral ligand (*R*)-**3** (89:11, entry 2). An even better selectivity was attained using chiral silylborane (−)-**2** and Pd/PPh_3 (94:6, entry 3). Further improvement of the enantioface selectivity was achieved under double-asymmetric induction conditions, in which both the silylborane and the ligand, (−)-**2** and (*R*)-**3**, were chiral (98:2, entry 4). On the other hand, a combination of (*R*)-**3** and enantiomeric silylborane (+)-**2** afforded a much lower selectivity (73:27, entry 5).

Next, silaboration of (*S*)-**4a** was carried out under the same reaction conditions (Table 2). The *Si*-face selective addition

Table 2. Silaboration of (*S*)-**4a**[a]



entry	silylborane	ligand	yield[b] (%)	(3*R*,4*S*)/(3*S*,4*S*)[c]
1	**1**	PPh_3	− (**5**)	33:67
2	**1**	(*R*)-**3**	97 (**5**)	78:22
3	(−)-**2**	PPh_3	96 (**6a**)	68:32
4	(−)-**2**	(*R*)-**3**	98 (**6a**)	94:6
5	(+)-**2**	(*R*)-**3**	(97)[d] (**6a′**)	42:58

[a] CpPd(η^3-allyl) (4.0 *μ*mol), ligand (4.8 *μ*mol), silylborane (0.40 mmol), and (*S*)-**4a** (0.48 mmol) were reacted in toluene (0.2 mL) at room temperature. [b] Isolated yield. [c] Determined by ^{1}H NMR. [d] Racemic mixture of **4a** was used for this entry. Isolated yield of a mixture of four diastereomers is shown.

under substrate-controlled silaboration using achiral reagents [(3*R*,4*S*)/(3*S*,4*S*) = 33:67, entry 1] was switched to a *Re*-

(2) For a synthesis of enantioenriched allylic silanes via intramolecular bis-silylation, see: (a) Suginome, M.; Iwanami, T.; Ohmori, Y.; Matsumoto, A.; Ito, Y. *Chem. Eur. J.* **2005**, *11*, 2954 and references therein. For a synthesis of enantioenriched allylic boranes via diboration, see: (b) Clegg, W.; Johann, T. R. F.; Marder, T. B.; Norman, N. C.; Orpen, A. G.; Peakman, T. M.; Quayle, M. J.; Rice, C. R.; Scott, A. J. *J. Chem. Soc., Dalton Trans.* **1998**, 1431. (c) Morgan, J. B.; Morken, J. P. *Org. Lett.* **2003**, *5*, 2573. (d) Pelz, N. F.; Woodward, A. R.; Burks, H. E.; Sieber, J. D.; Morken, J. P. *J. Am. Chem. Soc.* **2004**, *126*, 16328. For a synthesis of enantioenriched 1-boryl-4-silyl-2-cyclohexene via silaboration, see: (e) Gerdin, M.; Moberg, C. *Adv. Synth. Catal.* **2005**, *347*, 749.

(3) (a) Suginome, M.; Ohmori, Y.; Ito, Y. *Synlett* **1999**, 1567. (b) Suginome, M.; Ohmori, Y.; Ito, Y. *J. Organomet. Chem.* **2000**, *611*, 403. (c) Suginome, M.; Ohmori, Y.; Ito, Y. *J. Am. Chem. Soc.* **2001**, *123*, 4601. (d) Suginome, M.; Ohmori, Y.; Ito, Y. *Chem. Commun.* **2001**, 1090.

(4) Onozawa, S.-y.; Hatanaka, Y.; Tanaka, M. *Chem. Commun.* **1999**, 1863.

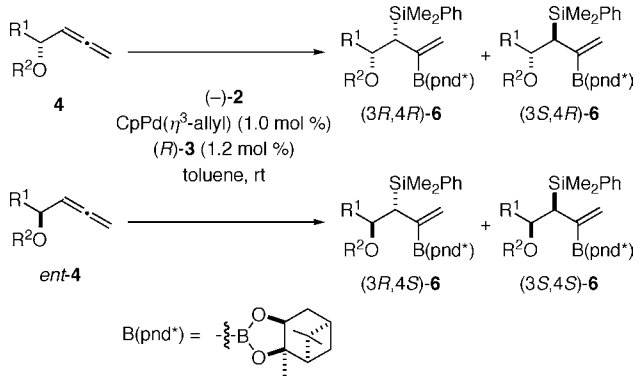
(5) (a) Hayashi, T.; Hirate, S.; Kitayama, K.; Tsuji, H.; Torii, A.; Uozumi, Y. *J. Org. Chem.* **2001**, *66*, 1441. (b) Hayashi, T. *Acc. Chem. Res.* **2000**, *33*, 354.

(6) Suginome, M.; Ohmura, T.; Miyake, Y.; Mitani, S.; Ito, Y.; Murakami, M. *J. Am. Chem. Soc.* **2003**, *125*, 11174.

face attack using the reagent-controlled conditions under which the chiral ligand (*R*)-**3** (78:22, entry 2) or the silylborane (−)-**2** (68:32, entry 3) was used. Although the enantioface selectivity was not particularly high using these reagent systems, the double-asymmetric induction system using (−)-**2** and (*R*)-**3** gave dramatically improved *Re*-face selectivity (94:6, entry 4). As observed in the silaboration of (*R*)-**4a**, the use of enantiomeric silylborane with (*R*)-**3** resulted in a much lower selectivity (42:58, entry 5). The results of the silaboration of (*R*)-**4a** and (*S*)-**4a** indicated that a combination of the silylborane (−)-**2** and the ligand (*R*)-**3** (or, obviously, (+)-**2** and (*S*)-**3**) was the best reagent system for the reagent-controlled stereodiscrimination.

The reagent system was applied to the silaboration of other α-alkoxyallenes (Table 3). To simplify the experimental

Table 3. Silaboration of α-Alkoxyallenes with (−)-**2** in the Presence of Pd/(*R*)-**3** Catalyst[a]



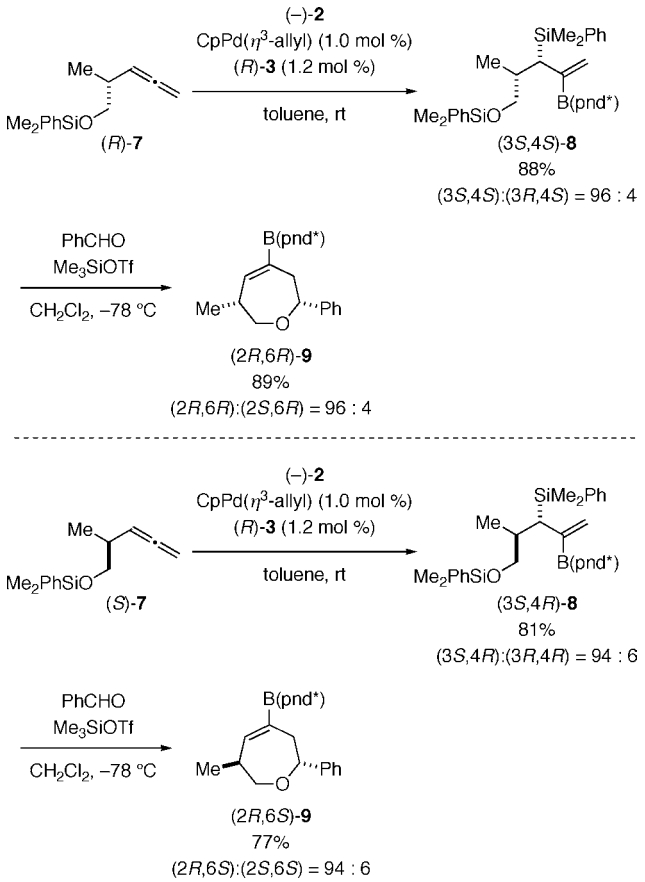
entry	R^1	R^2	yield[b] (%)	matched (3*R*,4*R*)/(3*S*,4*R*)[c]	mismatched (3*R*,4*S*)/(3*S*,4*S*)[c]
1	Me	Bn (**4b**)	94 (**6b**)	97:3	95:5
2	Me	Me_3Si (**4c**)	87 (**6c**)	98:2	93:7
3	Me	*t*-BuMe_2Si (**4d**)	90 (**6d**)	99:1	92:8
4	Et	Me_3Si (**4e**)	98 (**6e**)	98:2	93:7
5	*i*-Pr	Me_3Si (**4f**)	94 (**6f**)	97:3	93:7
6	Ph	Me_3Si (**4g**)	84 (**6g**)	97:3	92:8

[a] CpPd(η^3-allyl) (4.0 μmol), (*R*)-**3** (4.8 μmol), (−)-**2** (0.40 mmol), and **4** (0.48 mmol, racemic mixture) were reacted in toluene (0.2 mL) at room temperature. [b] Isolated yield of diastereomeric mixture. [c] Determined by ^1H NMR.

procedure, racemic α-alkoxyallenes were used in the presence of enantiopure (−)-**2** and (*R*)-**3**.[12] All of the reactions proceeded smoothly, giving the corresponding β-borylallylsilanes **6** in good yields. The enantioface selectivity of the matched enantiomers of the allenes ranged from 99:1 to 97:3. The allenes with smaller R^1 and larger R^2 tended to show a little higher selectivity (e.g., **4d**). On the other hand, the mismatched enantiomers of the allenes afforded enantioface selectivity ranging from 95:5 to 92:8. For this series of allenes, a higher selectivity was obtained when the allenes carried a smaller R^2 (e.g., **4b**). These results demonstrated the generality of the double asymmetric induction system using (−)-**2** and (*R*)-**3** to achieve the highly enantioface-selective silaboration of α-chiral terminal allenes.

The reagent system using (−)-**2** and (*R*)-**3** was also applicable to the silaboration of enantioenriched 5-dimethylphenylsilyl-4-methyl-1,2-pentadienes (*R*)-**7** and (*S*)-**7** (Scheme 1). As expected, the reactions of (*R*)-**7** and (*S*)-**7**

Scheme 1



yielded the corresponding β-borylallylsilanes (3*S*,4*S*)-**8** and (3*S*,4*R*)-**8**, respectively, with high enantioface selectivity (96:4 and 94:6, respectively). As a synthetic application of the resulting enantioenriched β-borylallylsilanes, the Markó-

(7) (a) Masamune, S.; Choy, W.; Petersen, J. S.; Sita, L. R. *Angew. Chem., Int. Ed. Engl.* **1985**, *24*, 1. (b) Kolodiazhnyi, O. I. *Tetrahedron* **2003**, *59*, 5953.

(8) For examples of reagent-controlled asymmetric reactions, see: (a) Katsuki, T.; Lee, A. W. M.; Ma, P.; Martin, V. S.; Masamune, S.; Sharpless, K. B.; Tuddenham, D.; Walker, F. J. *J. Org. Chem.* **1982**, *47*, 1373. (b) Brown, H. C.; Bhat, K. S.; Randad, R. S. *J. Org. Chem.* **1989**, *54*, 1570. (c) Reetz, M. T.; Rivadeneira, E.; Niemeyer, C. *Tetrahedron Lett.* **1990**, *31*, 3863. For examples of catalyst-controlled asymmetric reactions using chiral transition-metal catalysts, see: (d) Reetz, M. T.; Strack, T. J.; Mutulis, F.; Goddard, R. *Tetrahedron Lett.* **1996**, *37*, 9293. (e) Matsumura, K.; Hashiguchi, S.; Ikariya, T.; Noyori, R. *J. Am. Chem. Soc.* **1997**, *119*, 8738. (f) Chen, Q.; Kuriyama, M.; Soeta, T.; Hao, X.; Yamada, K.; Tomioka, K. *Org. Lett.* **2005**, *7*, 4439.

(9) Tatsuno, Y.; Yoshida, T.; Otsuka, S. *Inorg. Synth.* **1979**, *19*, 220.

(10) For preparation of **2**, see ref 6. For preparation of (*R*)-**3**, see: Uozumi, Y.; Suzuki, N.; Ogiwara, A.; Hayashi, T. *Tetrahedron* **1994**, *50*, 4293.

type intramolecular allylation with aldehydes via the generation of an oxonium intermediate was performed.[13] The reaction of enantioenriched **8** with benzaldehyde in the presence of trimethylsilyl triflate gave the seven-membered cyclic ethers **9** in good yields with retention of the boryl groups.[14] The diastereomeric ratios were 96:4 and 94:6, respectively, indicating that the cyclization proceeded via complete chirality transfer from the stereogenic centers α to the silyl group with no strong influence of the other stereogenic center.

In summary, we have demonstrated that the highly enantioface-selective silaboration of chiral α-substituted allenes proceeded with a chiral reagent system that consisted of silylborane (−)-**2** and an (*R*)-**3** ligand. The stereochemistry of the new stereogenic center in the product was efficiently controlled by a chiral reagent system with almost no influence of the stereochemistry of the stereogenic centers present in the starting allene.

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Supporting Information Available: Experimental procedures and characterization data of the products. This material is available free of charge via the Internet at http://pubs.acs.org.

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(11) **General Experimental Procedure.** Under an inert atmosphere, ligand (4.8 μmol) and CpPd(η^3-allyl) (4.0 μmol) were dissolved in toluene (0.2 mL). The mixture was stirred at room temperature for 15 min. Allene (0.48 mmol) and silylborane (0.40 mmol) were added sequentially to the reaction mixture, which was stirred at room temperature. After the reaction was completed, the volatile materials were evaporated. Bulb-to-bulb distillation in vacuo gave the products.

(12) The ratios of possible four diastereomers could be determined by ^{1}H NMR.

(13) (a) Markó, I. E.; Mekhalia, A. *Tetrahedron Lett.* **1992**, *33*, 1799. For related cyclization using enentioenriched allylsilanes, see: (b) Huang, H.; Panek, J. S. *J. Am. Chem. Soc.* **2000**, *122*, 9836. (c) Suginome, M.; Iwanami, T.; Ito, Y. *J. Am. Chem. Soc.* **2001**, *123*, 4356.

(14) The stereochemical assignment of the diastereomers of **9** was made tentatively on the basis of (1) well-established *anti*-S_E' stereochemical course of the reaction of α-chiral allylsilanes and (2) assumed trans configuration of the intermidiary oxonium ion.