Stereoselective Cross-Coupling Reaction of 2,4-Diaryl-1,1-diboryl-1,3-butadienes: Stereocontrolled Approach to 1,3,4,6-Tetraarylated 1,3,5-Hexatrienes

Masaki Shimizu,* Katsuhiro Shimono, Michael Schelper, Tamejiro Hiyama

Department of Material Chemistry, Graduate School of Engineering, Kyoto University, Kyoto University, Katsura, Nishikyo-ku, Kyoto 615-8510, Japan
Fax +81(75)3832445; E-mail: shimizu@npc05.kuic.kyoto-u.ac.jp

Received 7 April 2007

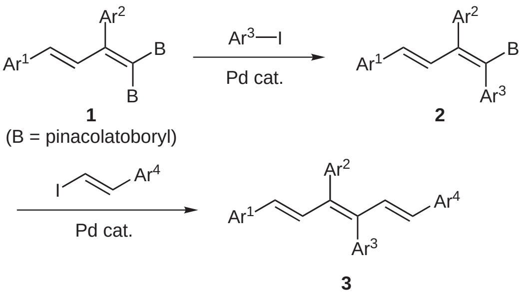
In memory of Professor Yoshihiko Ito

Abstract: The boryl group *cis* to the C(3)=C(4) group in 2,4-aryl-1,1-bis(pinacolatoboryl)-1,3-butadienes undergoes Pd-catalyzed cross-coupling reaction with aryl iodides stereoselectively at room temperature, giving rise to the corresponding boronates as a single diastereomer. Subsequent coupling of the boronates with alkenyl iodides allows us to synthesize 1,3,4,6-tetraarylated 1,3,5-hexatrienes stereoselectively.

Key words: alkenes, boron, cross-coupling, palladium, stereoselectivity

Much attention has been paid on π-conjugated organic molecules due to their photonic and electronic properties in such material science as molecular electronics.[1] Since those properties are closely relevant to their molecular structures, i.e. stereochemistry, synthetic methodologies for stereocontrolled π-conjugated system are essential for advance of organic functional materials. We have recently demonstrated that Pd-catalyzed cross-coupling reaction of 2-aryl-1,1-diboryl-1-alkenes with aryl iodides proceeds stereoselectively with the boryl group *cis* to the alkyl group.[2] Perfect discrimination of the two geminal boryl groups, induced by differences between alkyl and aryl groups, prompted us further to examine coupling reaction of alkenyl- and aryl-substituted 1,1-diborylethenes, which may provide polyfunctional π-conjugated molecules. We report herein the Pd-catalyzed coupling reaction of 2,4-aryl-1,1-bis(pinacolatoboryl)-1,3-butadienes **1** with aryl iodides Ar^3–I that gives rise to monocoupled product **2** with $Ar^1HC=CH$ and Ar^3 groups being *cis* as a single stereoisomer (Scheme 1). Further coupling reaction of **2** with alkenyl iodides $Ar^4CH=CHI$ allows us to establish a stereocontrolled approach to diverse 1,3,4,6-tetraarylated 1,3,5-hexatrienes **3**.

A THF solution of **1a** (Ar^1, Ar^2 = Ph, 1.0 equiv),[3] iodobenzene (1.1 equiv), and 3 M KOH aq (3.0 equiv) in the presence of $Pd(PPh_3)_4$ (5 mol%) was stirred at room temperature for eight hours.[4] Workup and purification by column chromatography on silica gel gave monocoupled



Scheme 1 Stereocontrolled approach to 1,3,4,6-tetraaryl-1,3,5-hexatrienes **3**

Table 1 Stereoselective Coupling Reaction of **1** with Aryl Iodides

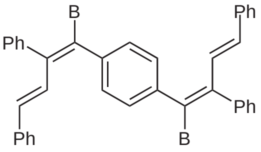
Entry	2	Ar^1	Ar^2	Ar^3	Yield (%)
1	**2a**[a]	Ph	Ph	Ph	76
2	**2b**[a]	Ph	Ph	$4\text{-}CF_3C_6H_4$	53
3	**2c**[a]	Ph	Ph	$4\text{-}EtO_2CC_6H_4$	49
4	**2d**[a]	Ph	Ph	$4\text{-}BrC_6H_4$	64
5	**2e**[a]	Ph	Ph	$4\text{-}PhC_6H_4$	45[b]
6	**2f**[a]	Ph	Ph	$4\text{-}MeOC_6H_4$	91
7	**2g**[c]	Ph	Ph	$2\text{-}MeOC_6H_4$	70
8	**2h**[c]	Ph	Ph	$3\text{-}MeOC_6H_4$	65
9	**2i**[c]	Ph	Ph	1-Naphthyl	72
10	**2j**[d]	Ph	Ph	3-Pyridyl	58
11	**2k**[c]	Ph	Ph	9-Phenan[e]	75
12	**2l**[a]	$4\text{-}MeOC_6H_4$	Ph	Ph	55
13	**2m**[a]	$4\text{-}MeOC_6H_4$	$4\text{-}MeOC_6H_4$	$4\text{-}CF_3C_6H_4$	58[f]
14	**2n**[g]	Ph	Ph	$1,4\text{-}C_6H_4$[h]	60

[a] $Pd(PPh_3)_4$ (5 mol%), 3 M KOH aq (3 equiv), THF, r.t.
[b] $4\text{-}PhC_6H_4Br$ was used.
[c] $PdCl_2(dppf)$ (5 mol%), 3 M KOH aq (3 equiv), DME, 40 °C.
[d] $PdCl_2(dppf)$ (5 mol%), 3 M KOH aq (3 equiv), THF, 40 °C.
[e] 9-Phenanthrenyl.
[f] 1*E*,3*E*:1*Z*,3*E* = 95:5.
[g] $Pd(PPh_3)_4$ (5 mol%), 3 M KOH aq (3 equiv), THF, 40 °C.
[h] 1,4-Phenylene.

SYNLETT 2007, No. 12, pp 1969–1971
Advanced online publication: 25.06.2007
DOI: 10.1055/s-2007-982567; Art ID: U03007ST

product **2a** as a single stereoisomer in 76% yield (Table 1, entry 1). Stereochemistry of **2a** was confirmed by X-ray crystal structure analysis, which disclosed that the coupling took place with the boryl group *cis* to the alkenyl group.[5] Under the same conditions, 4-substituted aryl iodides reacted with **1a** smoothly to give **2b**–**f** selectively (entries 2–6),[6] whereas coupling reaction of 2- and 3-methoxyphenyl, 1-naphthyl, 3-pyridyl, and 9-phenanthrenyl iodides were sluggish.

Fortunately, we were delighted to find that the iodides coupled with **1a** smoothly to produce **2g**–**k** in moderate to good yields, when $PdCl_2$(dppf) was used as a catalyst in DME or THF at 40 °C (entries 7–11). In all cases except for **2m** (1*E*,3*E*:1*Z*,3*E* = 95:5), monocoupled products **2** were isolated as a single stereoisomer (Figure 1).[6]



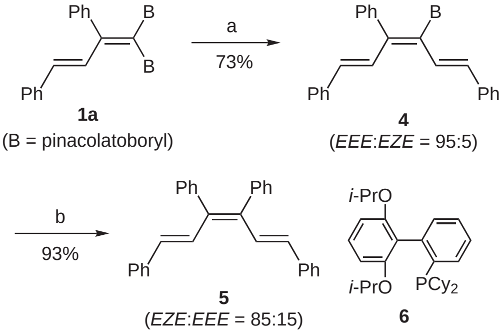
2n
(B = pinacolatoboryl)

Figure 1

The stereochemical outcome can be primarily understood by assuming that the reaction takes place with less-hindered boryl group, although electronic factors of alkenyl and aryl groups may also affect the differentiation.

Boronate **2a** reacted with alkenyl iodides (*E*)-PhCH=CHI in the presence of Pd[(*t*-Bu)$_3$P]$_2$ (8 mol%) and 3 M KOH aq (3 equiv) upon heating at 60 °C, giving rise to 1*E*,3*E*,5*E*-hexatrienes **3a** as a major isomer in excellent yield with high selectivity (Table 2, entry 1).[7] The stereochemistry of **3a** was confirmed by X-ray structure analysis of its single crystals.[5] Since longer reaction times caused lower diastereoselectivity of **3a**, 1*E*,3*Z*,5*E*-isomers were probably produced by isomerization of 1*E*,3*E*,5*E*-hexatrienes under the conditions. Under the same conditions, **2e**, **2i**, **2j**, **2l**, **2m**, and **2n** also coupled smoothly with alkenyl iodides to give **3** in good yields (except for **3g**) with high stereoselectivity (entries 2–7). Minor stereoisomers could be removed by recrystallization from hexane.

The present method is conveniently applicable to stereoselective synthesis of 3*Z*-isomer **5** simply by changing the order of electrophiles employed as demonstrated in Scheme 2. In this case, the best yield and diastereoselectivity of the first coupling were obtained with a $Pd_2(dba)_3$/phosphine **6** catalyst system.[8] The following coupling of **4** with iodobenzene gave **5** in 93% yield with slightly lowered diastereoselectivity (85:15), which was ascribed to isomerization of **5** under the conditions.



Scheme 2 Synthesis of 3*Z*-isomer **5**. *Reagents and conditions*: a) (*E*)-PhCH=CHI, $Pd_2(dba)_3$ (5 mol%), **6** (20 mol%), 3 M KOH aq (3 equiv), THF, r.t.; b) PhI, $PdCl_2$(dppf) (5 mol%), 3 M KOH aq (3 equiv), 60 °C.

Table 2 Synthesis of Tetraarylated 1,3,5-Hexatrienes **3**

Entry	**3**	Ar^1	Ar^2	Ar^3	Ar^4	Yield (%) (ratio)[a]
1	**3a**[b]	Ph	Ph	Ph	Ph	98 (96:4)
2	**3b**[b]	Ph	Ph	4-PhC$_6$H$_4$	Ph	84 (95:5)
3	**3c**[c]	Ph	Ph	1-Naphtyl	Ph	78 (94:6)
4	**3d**[b]	Ph	Ph	3-Pyridyl	Ph	70 (90:10)
5	**3e**[b]	4-MeOC$_6$H$_4$	Ph	Ph	4-CF$_3$C$_6$H$_4$	98 (96:4)
6	**3f**[b]	4-MeOC$_6$H$_4$	4-MeOC$_6$H$_4$	4-CF$_3$C$_6$H$_4$	4-CF$_3$C$_6$H$_4$	83 (91:9)
7	**3g**[c]	Ph	Ph	1,4-C$_6$H$_4$[d]	Ph	39 (>99:<1)

[a] Ratios of 1*E*,3*E*,5*E*/1*E*,3*Z*,5*E* isomers.
[b] Pd(*t*-Bu$_3$P)$_2$ (8 mol%), 3 M KOH aq (3 equiv), THF, 60 °C.
[c] 20 mol% of Pd(*t*-Bu$_3$P)$_2$ was used.
[d] 1,4-Phenylene.

Noteworthy is that solid **3a** and **3e** exhibit blue and yellow emission, respectively, by irradiation with UV light (365 nm).[9] In view that light emission in aggregated state of π-conjugated molecules is essential for application to electroluminescent materials, such observation is quite attractive for exploration of new emitting materials.[10]

In summary, we have demonstrated that the Pd-catalyzed cross-coupling reaction of 1,1-diboryl-1,3-butadienes with aryl iodides proceeded stereoselectively to give 1,2,4-triaryl-1-boryl-1,3-butadienes as a single diastereomer. In conjunction with the subsequent coupling with alkenyl iodides, the present method provides a convenient and stereocontrolled route to 1,3,4,6-tetraarylated 1,3,5-hexatrienes which may find application to light-emitting materials. Further studies on stereocontrolled preparation and optical properties of π-conjugated molecules are in progress in our laboratory.

Acknowledgment

This work was supported by Grant-in-Aid for Creative Scientific Research, No 16GS0209, from Ministry of Education, Culture, Sports, Science and Technology, Japan.

References and Notes

(1) (a) *Electronic Materials: The Oligomer Approach*; Müllen, K.; Wegner, G., Eds.; Wiley-VCH: Weinheim, **1998**.
(b) Tour, J. M. *Chem. Rev.* **1996**, *96*, 537. (c) Martin, R. E.; Diederich, F. *Angew. Chem. Int. Ed.* **1999**, *38*, 1350.
(d) Bendikov, M.; Wudl, F.; Perepichka, D. F. *Chem. Rev.* **2004**, *104*, 4891. (e) Nielsen, M. B.; Diederich, F. *Chem. Rev.* **2005**, *105*, 1837.

(2) Shimizu, M.; Nakamaki, C.; Shimono, K.; Schelper, M.; Kurahashi, T.; Hiyama, T. *J. Am. Chem. Soc.* **2005**, *127*, 12506.

(3) Diborylalkenes **1** were prepared by 1,1-diborylation of the corresponding 1,1-dibromo-1-alkenes with bis(pinacolato)diboron. See: (a) Hata, T.; Kitagawa, H.; Masai, H.; Kurahashi, T.; Shimizu, M.; Hiyama, T. *Angew. Chem. Int. Ed.* **2001**, *40*, 790. (b) Kurahashi, T.; Hata, T.; Masai, H.; Kitagawa, H.; Shimizu, M.; Hiyama, T. *Tetrahedron* **2002**, *58*, 6381
Compound **1a**: mp 119.9 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.00 (s, 12 H), 1.34 (s, 12 H), 6.20 (d, *J* = 15.6 Hz, 1 H), 7.20–7.36 (m, 10 H), 7.87 (d, *J* = 15.6 Hz, 1 H). ^{13}C NMR (67.8 MHz, $CDCl_3$): δ = 24.3, 25.0, 83.1, 83.2, 127.0, 127.6, 127.8, 128.5, 129.1, 132.4, 135.0, 137.5, 142.5, 163.6. IR (KBr): 2976, 2930, 2357, 2340, 1556, 1489, 1447, 1379, 1360, 1296, 1257, 1142, 984, 854, 756, 698 cm^{-1}. MS (EI, 70 eV): *m*/*z* (%) = 459 (8) [M$^+$ + 1], 458 (28) [M$^+$], 457 (13) [M$^+$ – 1], 330 (100). HRMS: *m*/*z* calcd for $C_{28}H_{36}B_2O_4$ [M$^+$]: 458.2800; found: 458.2794. Anal. Calcd for $C_{28}H_{36}B_2O_4$: C, 73.40; H, 7.92. Found: C, 73.41; H, 7.97.

(4) **Typical Procedure**
A solution of **1a** (0.10 g, 0.22 mmol), iodobenzene (47 mg, 0.23 mmol), $Pd(PPh_3)_4$ (13 mg, 0.011 mmol), and 3 M KOH aq (0.22 mL, 0.65 mmol) in THF (5 mL) was stirred at r.t. for 8 h before quenching with sat. aq NH_4Cl (20 mL). The aqueous layer was extracted with EtOAc (3 × 20 mL), washed with sat. NaCl aq (20 mL), and dried over anhyd $MgSO_4$. Removal of the organic solvents in vacuo followed by PTLC (hexane–EtOAc, 10:1) gave **2a** (72 mg, 76% yield) as a colorless solid; mp 98.0 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.00 (s, 12 H), 6.22 (d, *J* = 16.0 Hz, 1 H), 7.21–7.41 (m, 15 H). ^{13}C NMR (67.8 MHz, $CDCl_3$): δ = 24.4, 83.4, 126.5, 126.5, 126.7, 127.3, 127.6, 127.9, 128.1, 128.5, 128.8, 129.5, 130.2, 134.2, 137.4, 140.4, 141.6, 148.5. IR (KBr): 3051, 3023, 2976, 2928, 2362, 2343, 1952, 1730, 1595, 1576, 1491, 1442, 1360, 1308, 1267, 1213, 1142, 1074, 1024, 974, 859, 752, 700, 579 cm^{-1}. MS (EI, 70 eV): *m*/*z* (%) = 409 (21) [M$^+$ + 1], 408 (71) [M$^+$], 280 (100). HRMS: *m*/*z* calcd for $C_{28}H_{29}BO_2$ [M$^+$]: 408.2261; found: 408.2268. Anal. Calcd for $C_{28}H_{29}BO_2$: C, 82.36; H, 7.16. Found: C, 82.34; H, 7.16.

(5) Crystal data of **2a** and **3a** are deposited at Cambridge Crystallographic Data Centre as CCDC-619246 and CCDC-619193.

(6) Stereochemical assignment of **2b–n** is deduced from that of **2a**.

(7) **Typical Procedure**
A solution of **2a** (10 mg, 0.023 mmol), β-iodostyrene (8.0 mg, 0.035 mmol), $Pd[P(t\text{-}Bu)_3]_2$ (1.0 mg, 1.8 μmol, 8 mol%) and 3 M aq KOH solution (23 μL, 0.069 mmol) in THF (1 mL) was stirred at 60 °C for 12 h before quenching with sat. aq NH_4Cl solution (10 mL). The aqueous layer was extracted with EtOAc (3 × 10 mL), washed with sat. aq NaCl solution (10 mL). The organic layer was separated, dried over anhyd $MgSO_4$, and concentrated in vacuo. The residue was purified by preparative TLC (hexane–EtOAc, 10:1) to give **3a** (8.5 mg, 96% yield) as a 95:5 mixture of 1*E*,3*E*,5*E*- and 1*Z*,3*Z*,5*E*-isomers as a pale yellow solid. The recrystallization of the mixture from hexane gave (1*E*,3*E*,5*E*)-**3a**; mp 173.1 °C (hexane). R_f = 0.63 (hexane–EtOAc, 10:1). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 6.07 (d, *J* = 16.0 Hz, 2 H), 6.92 (d, *J* = 16.0 Hz, 2 H), 7.10–7.53 (m, 20 H). ^{13}C NMR (100 MHz, $CDCl_3$): δ = 126.5, 127.3, 127.4, 128.3, 128.5, 130.4, 130.8, 132.4, 137.6, 138.9, 141,0. IR (KBr): 3030, 1595, 1574, 1489, 1442, 1315, 1146, 1070, 1024, 961, 908, 750, 704, 689, 577, 556, 525 cm^{-1}. MS (EI, 70 eV): *m*/*z* (%) = 386 (7) [M$^+$ + 2], 385 (31) [M$^+$ + 1], 384 (100) [M$^+$]. HRMS: *m*/*z* calcd for $C_{30}H_{24}$ [M$^+$]: 384.1878; found: 384.1880. Anal. Calcd for $C_{30}H_{24}$: C, 93.71; H, 6.29. Found: C, 93.72; H, 6.53.

(8) Milne, J. E.; Buchwald, S. L. *J. Am. Chem. Soc.* **2004**, *126*, 13028.

(9) In contrast, a cyclohexane or $CHCl_3$ solution of **3a** exhibited no fluorescence. See: InTong, H.; Dong, Y.; Häusler, M.; Lam, J. W. Y.; Sung, H. H.-Y.; Williams, I. D.; Sun, J.; Tang, B. Z. *Chem. Commun.* **2006**, 1133.

(10) (a) Mitschke, U.; Bäuerle, P. *J. Mater. Chem.* **2000**, *10*, 1471. (b) Shirota, Y. *J. Mater. Chem.* **2005**, *15*, 75.