ORGANIC LETTERS

2009
Vol. 11, No. 9
1899−1902

Synthesis of B-Protected β-Styrylboronic Acids via Iridium-Catalyzed Hydroboration of Alkynes with 1,8-Naphthalenediaminatoborane Leading to Iterative Synthesis of Oligo(phenylenevinylene)s

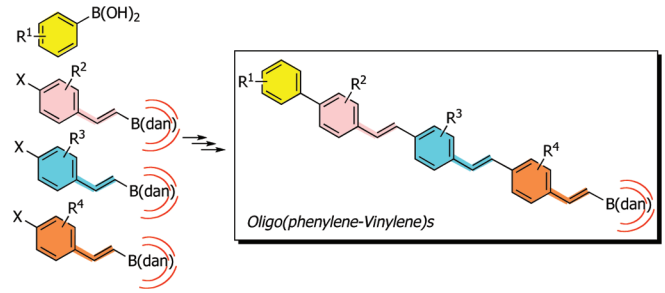
Noriyuki Iwadate and Michinori Suginome*

Department of Synthetic Chemistry and Biological Chemistry, Graduate School of Engineering, Kyoto University, Katsura, Kyoto 615-8510, Japan

suginome@sbchem.kyoto-u.ac.jp

Received February 12, 2009

ABSTRACT



Hydroboration of aromatic and aliphatic alkynes with 1,8-naphthalenediaminatoborane ((dan)BH) proceeded in the presence of $[IrCl(cod)]_2$ complex with a DPPM or DPEphos ligand, affording alkenylboronic acids whose boronyl groups are masked by the diaminonaphthalene group. The masked alkenylboronic acids thus obtained from alkynes bearing halo-substituted aryl groups served as new coupling modules in an iterative Suzuki−Miyaura cross-coupling reaction for the synthesis of oligo(phenylenevinylene)s.

Suzuki−Miyaura coupling is currently recognized as the most reliable, selective, and widely applicable cross-coupling reaction for the synthesis of conjugated organic molecules such as oligoarenes and arene-vinylene conjugates.[1,2] One of the major attractive features of the Suzuki−Miyaura coupling reaction over other cross-coupling reactions is the stability and availability of the organoboronic acid derivatives. In addition, recent progress in reactivity control by introduction of "protecting"[3−5] or "activating"[6] groups to the boron atoms of organoboronic acids allows new cross-coupling systems, which have rarely been achieved on the basis of other cross-coupling reactions.

We have been involved in the development of new protective groups for the boronyl groups ($B(OH)_2$) in the Suzuki−Miyaura coupling reaction.[4] We have established

(1) (a) Miyaura, N. *Top. Curr. Chem.* **2002**, *219*, 11. (b) Suzuki, A.; Brown, H. C. In *Organic Synthesis via Boranes*; Aldrich: Milwaukee, 2003; Vol. 3. (c) Miyaura, N.; Suzuki, A. *Chem. Rev.* **1995**, *95*, 2457.

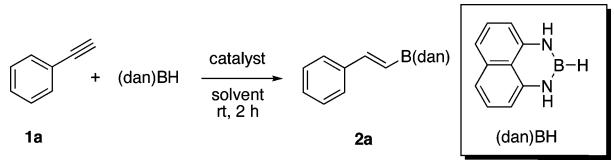
(2) (a) Tour, J. M. *Chem. Rev.* **1996**, *96*, 537. (b) Berresheim, A. J.; Müller, M.; Müllen, K. *Chem. Rev.* **1999**, *99*, 1747. (c) Segura, J. L.; Martin, N. *J. Mater. Chem.* **2000**, *10*, 1747. (d) Kraft, A.; Grimsdale, A. C.; Holmes, A. B. *Angew. Chem., Int. Ed.* **1998**, *37*, 402. (e) Schlüter, A. D. *J. Polym. Sci., Part A: Polym. Chem.* **2001**, *39*, 1533.

10.1021/ol9003096 CCC: $40.75
Published on Web 03/30/2009

that 1,8-diaminonaphthalene serves as a highly efficient protective agent for the boronyl groups in the Suzuki−Miyaura coupling, leading to the development of an iterative coupling system for oligoarene derivatives.[4,5,7] In our studies on the application of the boron-masking strategy to the iterative synthesis of oligo(phenylenevinylene)s, which are receiving increasing attention because of their light-emitting and NLO properties, it was desirable to establish a convenient and straightforward synthesis of the masked coupling modules. Although the masked modules may be prepared from the corresponding boronic acids via condensation with 1,8-diaminonaphthalene,[8] we decided to seek methods for direct introduction of the masked boronyl group into the organic molecules. Herein, we describe the synthesis of masked β-styrylboronic acids by hydroboration of alkynes with 1,8-naphthalenediaminatoborane ((dan)BH), whose reactivity has been established recently in Ir-catalyzed C−H borylation of arenes.[9] We also demonstrate the use of the masked β-styrylboronic acids in the synthesis of oligo(phenylenevinylene)s via iterative Suzuki−Miyaura coupling.

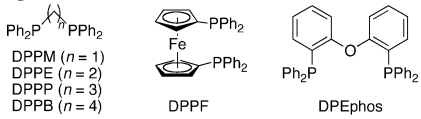
Hydroboration of phenylacetylene (**1a**) with (dan)BH was initially examined in the presence of rhodium and iridium catalysts (Table 1). Wilkinson's catalyst and the corresponding neutral rhodium/PPh_3 catalyst, which are known to be effective catalysts for hydroboration of alkynes with pinacolborane, showed only low catalytic activities (entries 1 and 2).[10] A cationic rhodium complex also failed to promote the hydroboration efficiently (entry 3). Our examination of iridium complexes showed that neutral iridium complexes had higher activities than the rhodium complexes (entries 5−11).[11,12] We observed a significant influence of the phosphine ligands on the catalytic activity and found that DPPM and DPEphos showed high catalytic activities (entries 6 and 11). The reaction in the presence of the iridium-DPEphos catalyst afforded *trans*-β-borylstyrene **2a** in 83% yield along with the corresponding *Z* stereoisomer and regioisomer in less than 5% yield each (90:5:5). The major isomer was easily separated from the other isomers by silica gel column chromatography. Although there observed no strong influence of the solvent on the reaction yields, hydroboration in CH_2Cl_2 was significantly faster than reactions in toluene, THF, dioxane, and acetonitrile (entries 12−15).

Table 1. Optimization of Hydroboration of Phenylacetylene with (dan)BH[a]



ent	catalyst	solvent	ligand	% yield of **4**[b]
1	$RhCl(PPh_3)_3$	CH_2Cl_2		5
2	$[RhCl(cod)]_2$	CH_2Cl_2	PPh_3	3
3	$[Rh(cod)_2]BF_4$	CH_2Cl_2	PPh_3	20
4	$[Ir(cod)_2]BF_4$	CH_2Cl_2	PPh_3	34
5	$[IrCl(cod)]_2$	CH_2Cl_2	PPh_3	50
6	$[IrCl(cod)]_2$	CH_2Cl_2	DPPM	81
7	$[IrCl(cod)]_2$	CH_2Cl_2	DPPE	76
8	$[IrCl(cod)]_2$	CH_2Cl_2	DPPP	60
9	$[IrCl(cod)]_2$	CH_2Cl_2	DPPB	26
10	$[IrCl(cod)]_2$	CH_2Cl_2	DPPF	61
11	$[IrCl(cod)]_2$	CH_2Cl_2	DPEphos	83
12	$[IrCl(cod)]_2$	toluene	DPEphos	76 (84)
13	$[IrCl(cod)]_2$	THF	DPEphos	68 (85)
14	$[IrCl(cod)]_2$	dioxane	DPEphos	59 (77)
15	$[IrCl(cod)]_2$	CH_3CN	DPEphos	52 (73)

[a] A mixture of **1**, alkyne (1.5 equiv), transition metal complex (5 mol % Rh or Ir), and ligand (6.0 mol %) in CH_2Cl_2 was stirred at room temperature for 2 h under a nitrogen atmosphere. [b] GC yield. Yields after 24 h are shown in the parentheses.



The optimized reaction conditions were applicable to the hydroboration of other alkynes (Table 2).[13] Arylacetylenes **1b**−**1g** bearing methyl, methoxy, dimethylamino, ethoxycarbonyl, and acetyl groups afforded the corresponding *trans*-products in good yields (entries 1−6). Note that electron-donating groups increased the reactivity of the triple bonds, allowing the reaction to proceed at room temperature, whereas arylacetylenes bearing an electron-withdrawing group needed 50 °C for the reaction to proceed (entries 5 and 6). Unsymmetrical, 1-phenylpropyne (**1h**) underwent the hydroboration in a regioselective manner, giving the β-styrylborane-type product **2h** with high regio- and stereoselectivity (entry 7). It should be noted that aliphatic alkynes **1i**−**1k** underwent hydroboration with **1** under the identical reaction conditions (entries 8−10). Cross-coupling modules **2l**−**2n**, which have bromine atoms at the *ortho*, *meta*, and *para* positions on the aromatic rings, could be synthesized by this reaction (entries 11−13). Substituted *p*-bromostyrene modules **2o** and **2p** could be prepared in good yields by hydroboration of the corresponding *p*-bromophenylacetylenes (entries 14 and 15). 2,5-Thiophenylethenyl module **2q** was also synthesized, albeit in moderate yield. Note that isomerically pure products were readily isolated by silica gel column chromatography in most cases, although stereo- and/

(3) (a) Molander, G. A.; Ellis, N. *Acc. Chem. Res.* **2007**, *40*, 275. (b) Molander, G. A.; Sandrock, D. L. *J. Am. Chem. Soc.* **2008**, *130*, 15792.

(4) (a) Noguchi, H.; Hojo, K.; Suginome, M. *J. Am. Chem. Soc.* **2007**, *129*, 758. (b) Noguchi, H.; Shioda, T.; Chou, C.-M.; Suginome, M. *Org. Lett.* **2008**, *10*, 377.

(5) (a) Gillis, E. P.; Burke, M. D. *J. Am. Chem. Soc.* **2007**, *129*, 6716. (b) Lee, S. J.; Gray, K. C.; Peak, J. S.; Burke, M. D. *J. Am. Chem. Soc.* **2008**, *130*, 466.

(6) Cyclic triolborates: (a) Yamamoto, Y.; Takizawa, M.; Yu, X.-Q.; Miyaura, N. *Angew. Chem., Int. Ed.* **2008**, *47*, 928. Trifluoroborates: (b) Molander, G. A.; Ellis, N. *Acc. Chem. Res.* **2007**, *40*, 275.

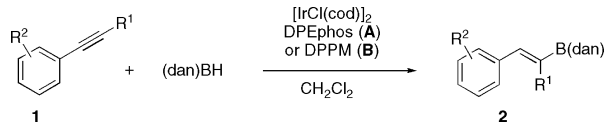
(7) (a) Ishikawa, S.; Manabe, K. *Chem. Lett.* **2006**, *35*, 164. (b) Ishikawa, S.; Manabe, K. *Chem. Commun.* **2006**, 2589.

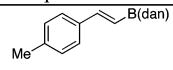
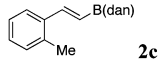
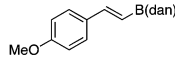
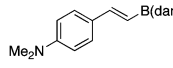
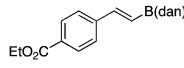
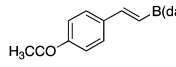
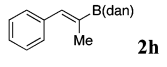
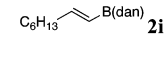
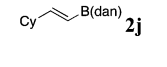
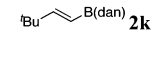
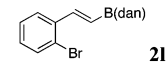
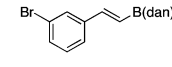
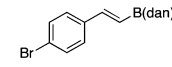
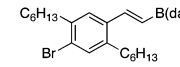
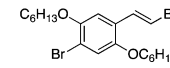
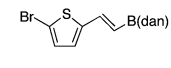
(8) For the syntheses and properties of PhB(dan), see: Kaupp, G.; Naimi-Jamal, M. R.; Stepanenko, V. *Chem.−Eur. J.* **2003**, *9*, 4156, and references therein.

(9) Iwadate, N.; Suginome, M. *J. Organomet. Chem.* **2009**, in press; DOI:, 10.1016/j.jorganchem.2008.11.068. For precedents of the preparation and reaction of (dan)BH, see: (b) Caserio, F. F., Jr.; Cavallo, J. J.; Wagner, R. I. *J. Org. Chem.* **1961**, *26*, 2157. (c) Smith, M. R., III. PCT WO 03/006158 A2.

(10) Mannig, D.; Noth, H. *Angew. Chem., Int. Ed. Engl.* **1985**, *24*, 878.

Table 2. Iridium-Catalyzed Hydroboration of Alkynes with (dan)BH[a]



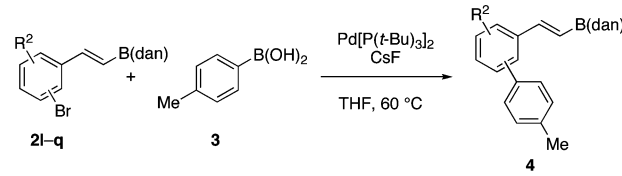
entry	product **2**	ligand	temp, time	% yield[b]
1	 **2b**	**A**	25 °C, 2 h	84
2	 **2c**	**A**	25 °C, 2 h	84
3	 **2d**	**A**	25 °C, 2 h	83
4	 **2e**	**A**	25 °C, 2 h	72
5	 **2f**	**A**	50 °C, 8 h	69
6	 **2g**	**A**	50 °C, 8 h	75
7	 **2h**	**B**	25 °C, 24 h	81
8	 **2i**	**A**	25 °C, 2 h	82 (10:1)[c]
9	 **2j**	**A**	25 °C, 2 h	80
10	 **2k**	**A**	25 °C, 2 h	65 (>20:1)[c]
11	 **2l**	**B**	50 °C, 12 h	63
12	 **2m**	**A**	25 °C, 12 h	63
13	 **2n**	**A**	50 °C, 8 h	81
14	 **2o**	**B**	50 °C, 8 h	80
15	 **2p**	**B**	50 °C, 8 h	70
16	 **2q**	**B**	50 °C, 8 h	41

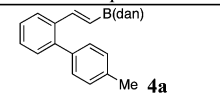
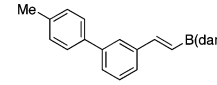
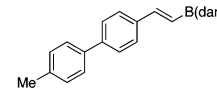
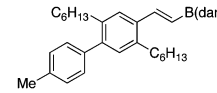
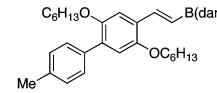
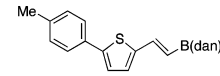
[a] A mixture of **1**, alkyne (1.5 equiv), $[IrCl(cod)]_2$ (5.0 mol % Ir), and ligand (6.0 mol %) in CH_2Cl_2 was stirred at 25 or 50 °C under a nitrogen atmosphere. [b] Isolated yield for isomerically pure material unless otherwise noted. [c] *Trans*:*cis*.

or regioisomers were formed in all the reactions (see Supporting Information).

The coupling modules **2l**−**2q** were used in Suzuki−Miyaura cross-coupling reactions (Table 3). Masked β-styrylboronic acids **2l**−**2n** having an *o*-, *m*-, or *p*-Br group underwent cross-coupling with *p*-tolylboronic acid in the presence of a $Pd[P(t\text{-}Bu)_3]_2$ catalyst to give the corresponding (β-borylalkenyl)biaryls **4a**−**4c** in good yields (entries 1−3).[14] The modules having alkyl and alkoxy side chains on the aromatic ring also underwent the coupling reaction in high

Table 3. Suzuki−Miyaura Coupling of Masked β-Styrylboronic Acids[a]



entry	masked module	product	% yield[b]
1	**2l**	 **4a**	83
2	**2m**	 **4b**	99
3	**2n**	 **4c**	87
4	**2o**	 **4d**	85
5	**2p**	 **4e**	86
6	**2q**	 **4f**	82

[a] See ref 13 for experimental details. [b] Isolated yield.

yields (entries 4 and 5). Thiophene module **2q** similarly afforded the corresponding aryl/thiophene/C=C ternary system **4f** in good yield (entry 6).

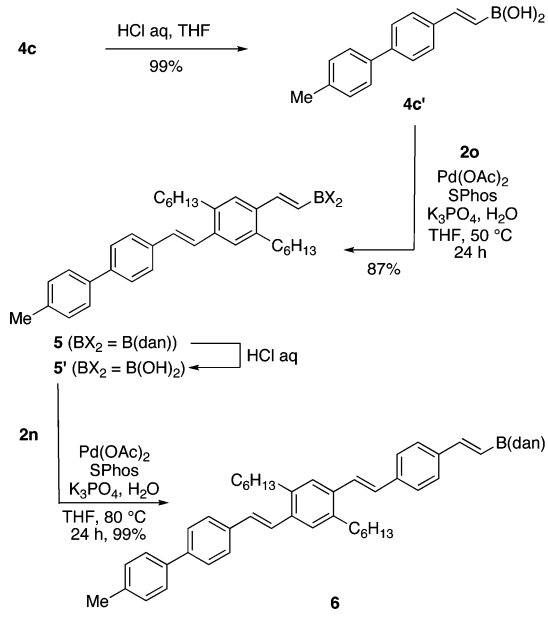
Using the divalent coupling modules **2n** and **2o** repeatedly, iterative synthesis of oligo(phenylenevinylene) (OPV hereafter) was demonstrated (Scheme 1). The dan group of the biaryl-vinyleneborane **4c** was unmasked by treatment with hydrochloric acid.[15] The unmasked alkeneboronic acid **4c′** was reacted with coupling module **2o**, which has alkyl chains on the aromatic core, in the presence of palladium/SPhos catalyst.[16,17] OPV **5** was isolated in 87% yield with perfect recovery of the protective group on the boronyl group. To obtain reproducible and good yields in the cross-coupling

(11) Ir-catalyzed hydroborations: (a) Evans, D. A.; Fu, G. C.; Hoveyda, A. H. *J. Am. Chem. Soc.* **1992**, *114*, 6671. (b) Yamamoto, Y.; Fujiwara, R.; Umemoto, T.; Miyaura, N. *Tetrahedron* **2004**, *60*, 10695.

(12) Reviews for catalytic hydroboration, see: (a) Beletskaya, I.; Pelter, A. *Tetrahedron* **1997**, *53*, 4957. (b) Burgess, K.; Ohlmeyer, M. J. *Chem. Rev.* **1991**, *91*, 1179. (c) Crudden, C. M.; Edwards, D. *Eur. J. Org. Chem.* **2003**, *24*, 4695. Asymmetric variants: (d) Hayashi, T. In *Comprehensive Asymmetric Catalysis*; Jacobsen, E. N., Pfaltz, A., Yamamoto, H., Eds.; Springer: Berlin, 1999; Vol. 1, p 351.

(13) Typical procedure for the hydroboration of alkynes with (dan)BH. Synthesis of **2o**. A mixture of $[IrCl(cod)]_2$ (15.8 mg, 24 μmol) and DPPM (21.7 mg, 56 μmol) in CH_2Cl_2 (4 mL) was stirred at rt for 10 min under a nitrogen atmosphere. (dan)BH (149 mg, 0.89 mmol) and 4-bromo-2,5-dihexylphenylacetylene (494 mg, 1.41 mmol) in CH_2Cl_2 (10 mL) was added to the solution. The mixture was stirred at 50 °C for 8 h. The resultant solution was evaporated under vacuum and purified by silica gel column chromatography (SiO_2 pretreated with 1% Et_3N in hexane, AcOEt/hexane 1:30), affording **2o** (368 mg, 80%).

Scheme 1. Iterative Synthesis of Oligo(phenylenevinylene) **6**



reaction using SPhos, it is important to add water (3.0 equiv) to the reaction system. When dry K_3PO_4 was used without adding water, the reaction proceeded only sluggishly.

After deprotection of the dan masking group, the third coupling was carried out with **2n**. The OPV **6** having three repeating phenylenevinylene units was obtained in high yield.

In summary, hydroboration of alkynes with 1,8-naphthalenediaminatoborane ((dan)BH) has been optimized and applied to the synthesis of oligo(phenylenevinylene)s via iterative Suzuki−Miyaura coupling. Among the transition metal catalysts, a neutral iridium(I) complex having bisphosphine ligands showed higher catalytic activities than rhodium catalysts, which are often used in the hydroboration with pinacolborane and catecholborane. Aryl alkynes having halogen groups on their aromatic rings were successfully hydroborated under the optimized reaction conditions, leading to the formation of masked coupling modules for the iterative cross-coupling reaction. The masked modules were unmasked with aqueous acids and coupled with organoboronic acids. Highly selective Suzuki−Miyaura cross-coupling took place with the protected boronyl group left intact. Synthesis of new coupling modules and their application to the synthesis of functionalized oligo(phenylenevinylene)s is now being undertaken in this laboratory.

Acknowledgment. This work was supported by Grant-in-Aid for Scientific Research from Ministry of Education, Culture, Sports, Science and Technology, Japan.

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

OL9003096

(14) Typical procedure for the cross-coupling reaction of **2**. Synthesis of **4c**. To a mixture of **2n** (49.2 mg, 0.141 mmol), *p*-tolylboronic acid (**3**) (19.2 mg, 0.141 mmol), and CsF (42.8 mg, 0.282 mmol) in THF (0.7 mL) was added $Pd(P^tBu_3)_2$ (1.44 mg, 0.00282 mmol) under a nitrogen atmosphere. The mixture was stirred at 60 °C for 4 h. After extraction with CH_2Cl_2, the organic phase was washed with brine and dried over Na_2SO_4. Filtration, evaporation, and purification by silica gel column chromatography (CH_2Cl_2/hexane 1:1 (5% NEt_3)) gave **4c** (42.0 mg, 87%).

(15) Typical procedure for the unmasking step. Synthesis of **4c′**. To a solution of **4c** (43 mg, 0.068 mmol) in THF (0.54 mL) was added hydrochloric acid (5 N, 54 μL, 0.27 mmol). The solution was stirred at room temperature for 4 h, resulting in precipitation of protonated 1,8-diaminonaphthalene. The suspension was filtered through a pad of Celite, and the solution was dried over K_2CO_3. Filtration and evaporation of the solvent in vacuo gave the corresponding boronic acid (35.3 mg, 99% yield) as a colorless solid. The boronic acid was used in the subsequent cross-coupling reaction without further purification.

(16) SPhos: 2-dicyclohexylphosphino-2′,6′-dimethoxy-1,1′-biphenyl. Barder, T. E.; Walker, S. D.; Martinelli, J. R.; Buchwald, S. L. *J. Am. Chem. Soc.* **2005**, *127*, 4685.

(17) Typical procedure for the cross-coupling using SPhos as a ligand. Synthesis of **5**. To a mixture of $Pd(OAc)_2$ (0.40 mg, 1.78 μmol), SPhos (1.46 mg, 3.56 μmol), **2o** (46.0 mg, 0.0899 mmol), **4c′** (21.2 mg, 0.0890 mmol), and K_3PO_4 (dried, 56.7 mg, 0.267 mmol) in THF (0.750 mL) was added H_2O (4.80 mg, 0.267 mmol) under a nitrogen atmosphere. The mixture was stirred at 50 °C for 24 h. After extraction with CH_2Cl_2, the organic phase was washed with brine and dried over Na_2SO_4. Filtration, evaporation, and purification by silica gel column chromatography (pretreated with 1% NEt_3 in hexane, CH_2Cl_2/hexane 1:5) gave coupling product **5** (48.8 mg, 87%).