Synthetic Methods

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Copper-Catalyzed Stereoselective Aminoboration of Bicyclic Alkenes**

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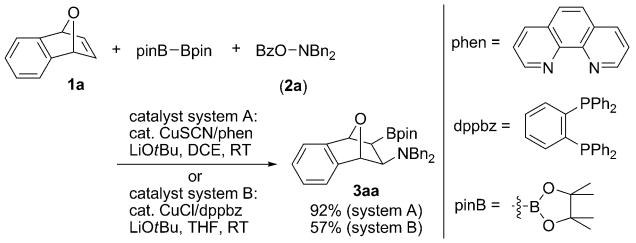
Abstract: *A copper-catalyzed aminoboration of bicyclic alkenes, including oxa- and azabenzonorbornadienes, has been developed. With this method, amine and boron moieties are simultaneously introduced at an olefin with exo selectivity. Subsequent stereospecific transformations of the boryl group can provide oxygen- and nitrogen-rich cyclic molecules with motifs that may be found in natural products or pharmaceutically active compounds. Moreover, a catalytic asymmetric variant of this transformation was realized by using a copper complex with a chiral bisphosphine ligand, namely (R,R)-Ph-BPE.*

Densely functionalized cyclic molecules with oxygen and nitrogen functional groups are frequently occurring substructures in biologically active compounds and natural products. The catalytic difunctionalization of cyclic olefins is one of the most attractive approaches to these molecules because of its straightforwardness and versatility. Bicyclic alkenes, in particular oxa- and azabicycloalkenes, are suitable starting materials to access the above-mentioned target structures in a stereoselective manner.[1] Whereas a variety of nucleophilic ring-opening reactions have been developed, the simultaneous introduction of two functional groups to a carbon–carbon double bond is still challenging.[2] To the best of our knowledge, hydroxylative and aminative difunctionalizations have remained particularly underdeveloped. Given their capability of rapidly increasing the molecular complexity and the number of chiral centers of a given substrate, the development of new catalyst systems for the stereoselective difunctionalization of bicyclic alkenes is appealing. Herein, we report a copper-catalyzed aminoboration of bicycloalkenes, including oxa- and azabenzonorbornadienes, with diboron reagents and hydroxylamines. This transformation adds the amine and boron functional groups across the olefinic moiety in one synthetic operation to form the corresponding aminoborated products in good yields with perfect *exo* selectivity. Subsequent oxidative transformations of the boryl group can provide oxygen- and nitrogen-rich alicyclic compounds with high diastereoselectivity. Moreover, the use of an appropriate chiral bisphosphine ligand renders the reaction enantioselective, delivering optically active products in good enantiomeric ratios (e.r.).

As part of our studies on umpolung-enabled electrophilic amination reactions,[3,4] we selected *O*-benzoyl-*N*,*N*-dibenzylhydroxylamine (**2a**) and bis(pinacolato)diboron (pinB–Bpin) as an electrophilic amination reagent and a nucleophilic boryl source,[5] respectively, and began optimization studies for the catalytic aminoboration of a model bicyclic substrate, namely oxabenzonorbornadiene **1a** (see the Supporting Information for details). After extensive screening of metal salts, ligands, bases, and solvents, we were pleased to identify two effective catalyst systems. System A comprises the use of CuSCN, 1,10-phenanthroline (phen), and LiO*t*Bu in 1,2-dichloroethane (DCE), whereas under conditions B, CuCl, 1,2-bis(diphenylphosphino)benzene (dppbz), and LiO*t*Bu are employed in THF (Scheme 1). Under either set of reaction conditions, the reaction proceeded without the formation of ring-opened side products,[1] and only *exo* adduct **3aa** was obtained.



Scheme 1. Copper-catalyzed stereoselective aminoboration of oxabenzonorbornadiene **1a** with *O*-benzoyl-*N*,*N*-dibenzylhydroxylamine (**2a**) and pinB–Bpin. Bn = benzyl, Bz = benzoyl.

With the optimized conditions in hand, we studied the aminoboration of various bicyclic alkenes **1** with **2a** and pinB–Bpin (Table 1). Notably, fine-tuning of the reaction stoichiometry was essential for satisfactory yields in each case, and the most suitable catalyst system (A or B) was highly dependent on the electronic and steric nature of the bicycloalkene employed. For example, electron-rich methoxy-substituted oxabenzonorbornadienes **1b** and **1e** as well as electron-neutral **1a** showed higher reactivity under conditions A (entries 2 and 5), whereas catalyst system B was more suitable for the reaction of electron-deficient substrates **1c** and **1d**, which bear fluoro and bromo moieties (entries 3 and 4). In the case of **1d**, the aminoborated product **3da** was formed with the C–Br moiety left intact, which can be a useful synthetic handle for further manipulations by conventional

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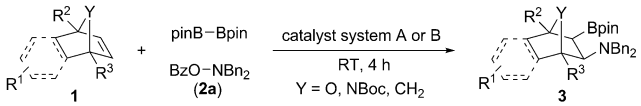
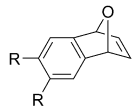
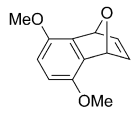
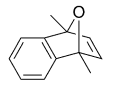
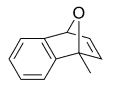
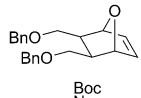
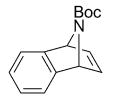
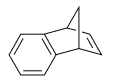
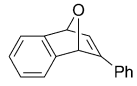
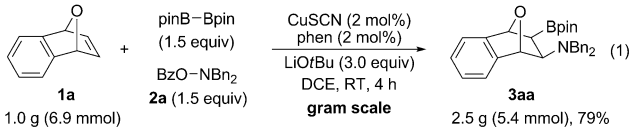
Table 1: Copper-catalyzed aminoboration of various bicyclic alkenes **1** with *O*-benzoyl-*N*,*N*-dibenzylhydroxylamine (**2a**).[a]



Entry	**1**		Cond.	**3**	Yield[b] [%]
1		R = H: **1a**	A	**3aa**	92 (69)[c]
2		R = OMe: **1b**	A	**3ba**	76
3		R = F: **1c**	B	**3ca**	56
4		R = Br: **1d**	B	**3da**	54
5		**1e**	A	**3ea**	88
6		**1f**	A	**3fa**	92
7		**1g**	A	**3ga**	91[d]
8		**1h**	A	**3ha**	81
9		**1i**	A	**3ia**	99
10		**1j**	B	**3ja**	92
11[e]		**1k**	B	**3ka**	81
12		**1l**	B	**3la**	78
13[f]		**1a**	A	**3aa**-Bneo	41
14		**1m**	A	**3ma**	0

[a] Conditions A: **1** (0.25 mmol), **2a** (1.5–4.0 equiv), pinB−Bpin (1.5–4.0 equiv), LiO*t*Bu (2.0–4.0 equiv), CuSCN (5–10 mol%), phen (5–10 mol%), DCE (1.5 mL), RT, 4 h. Conditions B: **1** (0.25 mmol), **2a** (2.0–4.0 equiv), pinB−Bpin (2.0–4.0 equiv), LiO*t*Bu (2.0–4.0 equiv), CuCl (10 mol%), dppbz (10 mol%), THF (1.5 mL), RT, 4 h. See the Supporting Information for details. [b] Yields of isolated products are given. [c] Catalyst loading: 2 mol%. [d] Regioisomer **3ga′** was also detected by ^{1}H NMR spectroscopy (**3ga**/**3ga′** = 20:1). [e] **1k** (0.75 mmol), **2a** (0.25 mmol). [f] With neoB−Bneo instead of pinB−Bpin. Boc = *tert*-butoxycarbonyl.

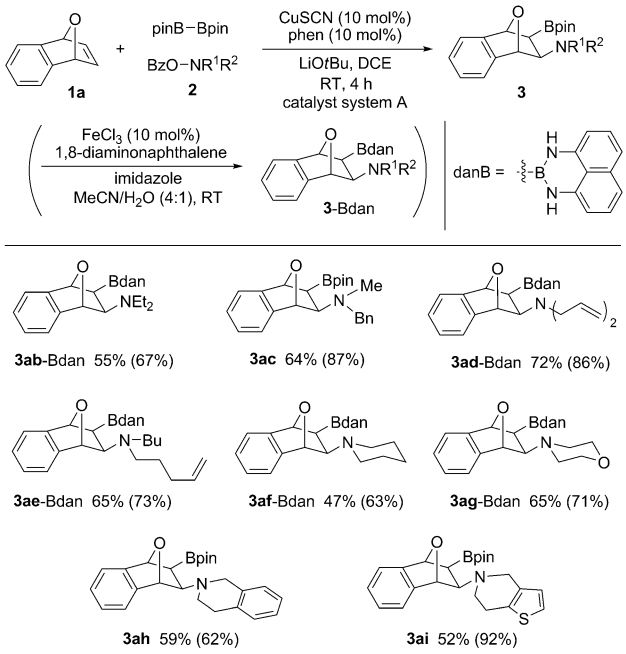
palladium catalysis (entry 4). Furthermore, substituents at the bridgehead position were also tolerated under conditions A (entries 6 and 7). It is noteworthy that the unsymmetric alkene **1g** afforded **3ga** with high regioselectivity, in which the Bpin added preferentially at the position far from the methyl group (entry 7). Non-benzene-fused oxabicyclic alkene **1h** also underwent the catalytic aminoboration without difficulties to furnish **3ha** in 81% yield (entry 8). Moreover, the reactions worked well for several aza- and methylene-bridged analogues: **1i** and **1j** were smoothly transformed into **3ia** and **3ja** in 99 and 92% yield under conditions A and B, respectively (entries 9 and 10). Simple norbornadiene (**1k**) and norbornene (**1l**) were also suitable substrates for the aminoboration (entries 11 and 12), but the former substrate necessitated the use of hydroxylamine **2a** as the limiting agent to suppress the overreaction of the second olefinic moiety. As the boryl source, neoB−Bneo (neo = neopentylglycolato) could also be used, but led to a moderate yield (entry 13). Notably, the catalyst loading could be reduced to 2 mol% (entry 1), and the synthesis of **3aa** was possible on gram scale [Eq. (1)], which highlights the good reproducibility and



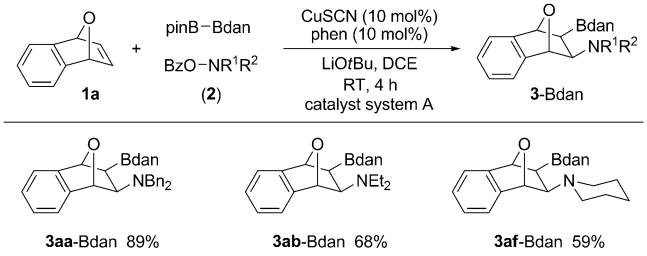
practicability of the aminoboration reaction. A current limitation of this transformation is that trisubstituted olefins may not be employed as substrates (entry 14).

We subsequently subjected an array of *O*-benzoylhydroxylamines to the catalytic aminoboration with **1a** and pinB−Bpin. The reaction itself proceeded well, but some products were less stable, and the purification step could be problematic. In such cases, we converted the crude materials into the more stable Bdan (dan = 1,8-diaminonaphthalenyl)[6] derivatives by iron catalysis under previously reported conditions;[7] these products were then isolated by column chromatography (see the Supporting Information for the detailed procedure). Representative results are summarized in Scheme 2. Catalyst system A was compatible with acyclic amines, including *N*,*N*-diethyl-, *N*-benzyl-*N*-methyl-, and *N*,*N*-diallylamines (**3ab**-Bdan, **3ac**, and **3ad**-Bdan). The benzyl and allyl groups in **3ac** and **3ad**-Bdan can be removed under appropriate conditions,[8] and the free NH moieties might be useful synthetic handles for additional synthetic elaborations. The formation of the usual aminoborated product **3ae**-Bdan, which is not accompanied by the formation of pyrrolidine-containing side products, suggests that a pathway proceeding via an aminyl radical (or its copper-coordinated form) is unlikely.[9] The catalytic aminoboration of several cyclic and bicyclic amines also proceeded under identical conditions to form piperidine-, morpholine-, tetrahydroisoquinoline-, and thienopiperidine-substituted oxabenzonorbornenylboranes in synthetically useful yields (**3af**-Bdan, **3ag**-Bdan, **3ah**, and **3ai**).

As mentioned above, some aminoborated products were difficult to handle in the Bpin form. Thus, we attempted the reaction with pinB−Bdan[6c] in place of pinB−Bpin (Scheme 3). Pleasingly, pinB−Bdan worked as well as pinB−Bpin under otherwise identical conditions, and the Bdan group was selectively incorporated into the product.[10] In particular, the yields of diethylamine- and piperidine-containing **3ab**-Bdan and **3af**-Bdan increased by approximately 10%, compared to those obtained with pinB−Bpin (Scheme 2 vs. Scheme 3).



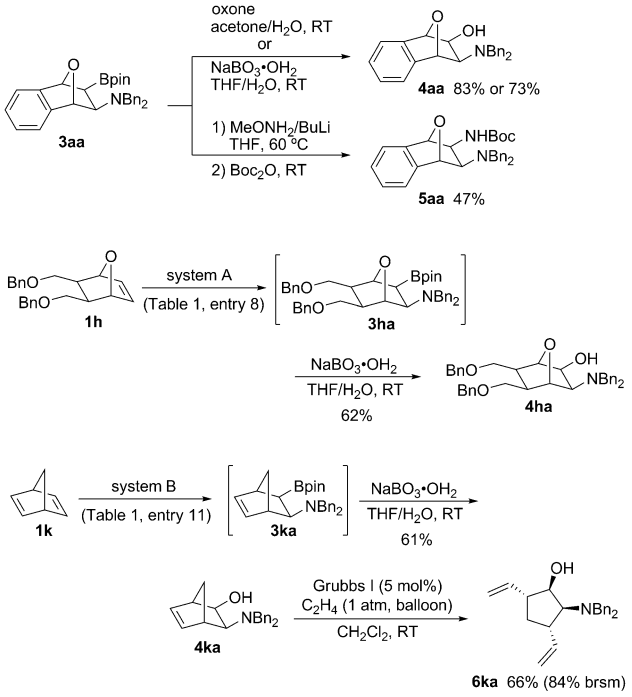
Scheme 2. Copper-catalyzed aminoboration of oxabenzonorbornadiene **1a** with various *O*-benzoylhydroxylamines **2** and pinB–Bpin. For details on the reaction conditions, see the Supporting Information. Yields of isolated products are given. Yields of the Bpin derivatives were determined by ^{1}H NMR spectroscopy and are given in parentheses.



Scheme 3. Copper-catalyzed aminoboration of oxabenzonorbornadiene **1a** with various *O*-benzoylhydroxylamines **2** and pinB–Bdan. For details on the reaction conditions, see the Supporting Information. Yields of isolated products are given.

The following transformations of the aminoborated products, which make use of the boron moiety, demonstrate the synthetic utility of the catalytic aminoboration (Scheme 4). The hydroxylation (oxone/acetone)[11] and amination ($MeONH_2$/BuLi/Boc_2O)[4j] of **3aa** afforded aminoalcohol **4aa** and diamine **5aa**, respectively, in acceptable overall yields. For the preparation of **4aa**, $NaBO_3{\cdot}OH_2$ could be used as an alternative oxidant. The same synthetic sequence could be applied to **1h** to yield **4ha**. Moreover, in the case of aminoalcohol **4ka**, which is derived from norbornadiene (**1k**), subsequent ring-opening cross-metathesis with ethylene in the presence of Grubbs I catalyst enabled the stereospecific formation of multifunctionalized cyclopentane skeleton **6ka**.[12]

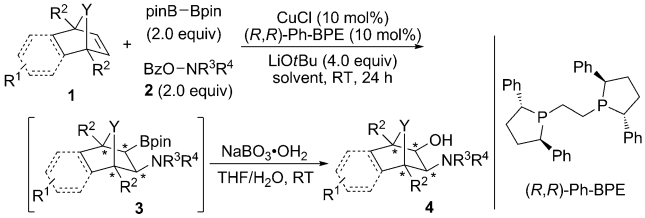
While preliminary, we also succeeded in the asymmetric synthesis of some aminoborated products **3** by using an



Scheme 4. Transformations of aminoborated products **3**. brsm = based on recovered starting material.

optically active bisphosphine ligand (Table 2). The catalytic enantioselective aminoboration of **1a** with **2a** proceeded in the presence of a CuCl/(*R*,*R*)-Ph-BPE complex in 1,4-dioxane to furnish **3aa** in 67% yield with 94:6 e.r. (entry 1; see the Supporting Information for detailed optimization studies). For fluorine-substituted oxabenzonorbornadiene **1c**, THF was the best solvent, and **3ca** was obtained in 96:4 e.r. (entry 2). *N*-Benzyl-*N*-methylhydroxylamine **2c** was also a suitable substrate for this asymmetric transformation (**3ac**,

Table 2: Enantioselective aminoboration of bicyclic alkenes **1** with **2** and pinB–Bpin.[a]

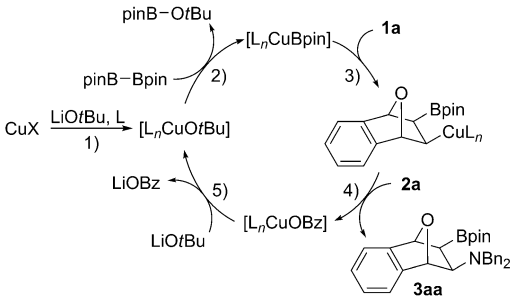


Entry	1	2	Solvent	3, yield [%][b]	4, yield [%],[c] e.r.
1	**1a**	**2a**	1,4-dioxane	**3aa**, 67	**4aa**, 43, 94:6
2	**1c**	**2a**	THF	**3ca**, 47	**4ca**, 39, 96:4
3	**1a**	**2c**	1,4-dioxane	**3ac**, 69	**4ac**, 17, 94:6
4	**1i**	**2a**	1,4-dioxane	**3ia**, 50	**4ia**, 35, 89:11
5	**1j**	**2a**	THF	**3ja**, 92	**4ja**, 66, 94:6

[a] Reaction conditions: **1** (0.25 mmol), **2** (0.50 mmol), pinB–Bpin (0.50 mmol), LiO*t*Bu (1.0 mmol), CuCl (0.025 mmol), (*R*,*R*)-Ph-BPE (0.025 mmol), solvent (1.5 mL), RT, 24 h. Conditions for the oxidation of the crude product (not optimized): $NaBO_3{\cdot}OH_2$ (1.4 mmol), THF (0.60 mL), H_2O (0.60 mL), open flask. [b] Yields determined by ^{1}H NMR spectroscopy. [c] Yields of isolated products based on starting material **1**.

69%, 94:6 e.r.; entry 3). The chiral Cu catalyst also effectively enabled the enantioselective formation of aza- and methylene-bridged **3ia** (50%, 89:11 e.r.; entry 4) and **3ja** (92%, 94:6 e.r.; entry 5). The absolute configuration of **3aa** was confirmed to be 1*S*,2*R*,3*S*,4*S* by X-ray analysis after derivatization to the corresponding bromine-containing ester, and the absolute configurations of the other products were tentatively assigned by analogy.[13]

Although the exact reaction pathway remains to be elucidated, based on our findings and literature precedents, one possibility involves 1) the initial off-cycle formation of a [L_nCuO*t*Bu] species from the Cu salt, ligands, and LiO*t*Bu,[14] 2) σ-bond metathesis with pinB–Bpin generating a [L_nCuBpin] intermediate,[15] 3) coordination and insertion of the bicycloalkene **1a** into the Cu–B bond[16] from the less congested convex face, 4) electrophilic amination[4] with hydroxylamine **2a** liberating the aminoborated product **3aa** and a [L_nCuOBz] complex, and 5) closing the catalytic cycle by ligand exchange of [L_nCuOBz] with LiO*t*Bu[17] (Scheme 5).



Scheme 5. Plausible reaction mechanism for the aminoboration of **1a** with **2a** and pinB–Bpin. L = ligand.

Both the *exo* selectivity and the enantioselectivity are determined during the insertion step (3), and C–N bond formation with retention of stereochemistry[3i,4g] in the subsequent step (4) delivers the final product with the observed stereochemistry. However, the crucial interactions in the enantioselectivity-determining step are still unclear. Further efforts to clarify the mechanism are ongoing.

In conclusion, we have developed a copper-catalyzed aminoboration of bicyclic alkenes, including oxa- and azabenzonorbornadienes, with diboron reagents and hydroxylamines. Combined with subsequent stereospecific transformations that make use of the resultant boron moiety as well as a ring-opening reaction, this transformation constitutes a rapid and concise approach to oxygen- and nitrogen-rich cyclic molecules that might be of interest in pharmaceutical and medicinal chemistry. Furthermore, an asymmetric variant has also been achieved by the use of a chiral bisphosphine/copper catalyst. Further product manipulations, such as cross-couplings or stereospecific ring-opening reactions of the oxa- and azabicycles, and related aminoboration reactions are currently being developed in our laboratory.

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[1] For selected accounts and reviews, see: a) M. Lautens, K. Fagnou, S. Hiebert, *Acc. Chem. Res.* **2003**, *36*, 48; b) D. K. Rayabarapu, C.-H. Cheng, *Acc. Chem. Res.* **2007**, *40*, 971; c) C. Bournaud, F. Chung, A. P. Luna, M. Pasco, G. Errasti, T. Lecourt, L. Micouin, *Synthesis* **2009**, 869.

[2] A limited amount of successful examples of the catalytic difunctionalization of heteroatom-bridged bicyclic alkenes have been reported; for cycloaddition reactions with alkynes, arynes, or diynes, see: a) K. C. Chao, D. K. Rayabarapu, C. C. Wang, C.-H. Cheng, *J. Org. Chem.* **2001**, *66*, 8804; b) T. Sambaiah, D. J. Huang, C.-H. Cheng, *J. Chem. Soc. Perkin Trans. 2* **2000**, 195; c) T. T. Jayanth, M. Jeganmohan, C.-H. Cheng, *J. Org. Chem.* **2004**, *69*, 8445; d) G.-C. Ge, D.-L. Mo, C.-H. Ding, L.-X. Dai, X.-L. Hou, *Org. Lett.* **2012**, *14*, 5756; for multicomponent couplings with aryl iodides and terminal alkynes, see: e) C.-J. Kuo, S.-J. Cheng, S.-T. Chang, C.-H. Liu, *Eur. J. Org. Chem.* **2008**, 485; metal-catalyzed ring-retaining carbometalations followed by trapping with additional external electrophiles have also been reported; see: f) M. Lautens, S. Hiebert, J.-L. Renaud, *J. Am. Chem. Soc.* **2001**, *123*, 6834; g) M. Lautens, S. Hiebert, *J. Am. Chem. Soc.* **2004**, *126*, 1437; h) S. Ito, T. Itoh, M. Nakamura, *Angew. Chem. Int. Ed.* **2011**, *50*, 454; *Angew. Chem.* **2011**, *123*, 474.

[3] For our recent work on electrophilic aminations by umpolung, see: a) T. Kawano, K. Hirano, T. Satoh, M. Miura, *J. Am. Chem. Soc.* **2010**, *132*, 6900; b) K. Hirano, T. Satoh, M. Miura, *Org. Lett.* **2011**, *13*, 2395; c) N. Matsuda, K. Hirano, T. Satoh, M. Miura, *Org. Lett.* **2011**, *13*, 2860; d) N. Matsuda, K. Hirano, T. Satoh, M. Miura, *J. Org. Chem.* **2012**, *77*, 617; e) N. Matsuda, K. Hirano, T. Satoh, M. Miura, *Angew. Chem. Int. Ed.* **2012**, *51*, 3642; *Angew. Chem.* **2012**, *124*, 3702; f) N. Matsuda, K. Hirano, T. Satoh, M. Miura, *Synthesis* **2012**, 1792; g) N. Matsuda, K. Hirano, T. Satoh, M. Miura, *Angew. Chem. Int. Ed.* **2012**, *51*, 11827; *Angew. Chem.* **2012**, *124*, 11997; h) Y. Miki, K. Hirano, T. Satoh, M. Miura, *Org. Lett.* **2013**, *15*, 172; i) N. Matsuda, K. Hirano, T. Satoh, M. Miura, *J. Am. Chem. Soc.* **2013**, *135*, 4934; j) R. Sakae, K. Hirano, T. Satoh, M. Miura, *Chem. Lett.* **2013**, *42*, 1128; k) Y. Miki, K. Hirano, T. Satoh, M. Miura, *Angew. Chem. Int. Ed.* **2013**, *52*, 10830; *Angew. Chem.* **2013**, *125*, 11030; l) R. Sakae, K. Hirano, T. Satoh, M. Miura, *Org. Lett.* **2014**, *16*, 1228; m) Y. Miki, K. Hirano, T. Satoh, M. Miura, *Org. Lett.* **2014**, *16*, 1498; n) K. Hirano, M. Miura, *Pure Appl. Chem.* **2014**, *86*, 291.

[4] For reviews on electrophilic aminations, see: a) E. Erdik, M. Ay, *Chem. Rev.* **1989**, *89*, 1947; b) K. Narasaka, M. Kitamura, *Eur. J. Org. Chem.* **2005**, 4505; c) E. Ciganek, *Org. React.* **2009**, *72*, 1; d) T. J. Barker, E. R. Jarvo, *Synthesis* **2011**, 3954; e) M. Corpet, C. Gosmini, *Synthesis* **2014**, 2258; for selected examples, see: f) A. M. Berman, J. S. Johnson, *J. Am. Chem. Soc.* **2004**, *126*, 5680; g) M. J. Campbell, J. S. Johnson, *Org. Lett.* **2007**, *9*, 1521; h) S. Liu, L. S. Liebeskind, *J. Am. Chem. Soc.* **2008**, *130*, 6918; i) T. J. Barker, E. R. Jarvo, *J. Am. Chem. Soc.* **2009**, *131*, 15598; j) S. N. Mlynarski, A. S. Karns, J. P. Morken, *J. Am. Chem. Soc.* **2012**, *134*, 16449; see the Supporting Information for a complete list of references.

[5] For recent advances in the nucleophilic borylation of unsaturated C–C bonds with pinB–Bpin, see: a) Y. Lee, A. H. Hoveyda, *J. Am. Chem. Soc.* **2009**, *131*, 3160; b) Y. Sasaki, C. Zhong, M. Sawamura, H. Ito, *J. Am. Chem. Soc.* **2010**, *132*, 1226; c) L. Zhang, J. Cheng, B. Carry, Z. Hou, *J. Am. Chem. Soc.* **2012**,

134, 14314; d) R. Alfaro, A. Parra, J. Alemán, J. L. G. Ruano, M. Tortosa, *J. Am. Chem. Soc.* **2012**, *134*, 15165; e) Y. Takemoto, H. Yoshida, K. Takaki, *Chem. Eur. J.* **2012**, *18*, 14841; f) K. Kubota, E. Yamamoto, H. Ito, *J. Am. Chem. Soc.* **2013**, *135*, 2635; g) K. Semba, T. Fujiwara, J. Terao, Y. Tsuji, *Angew. Chem. Int. Ed.* **2013**, *52*, 12400; *Angew. Chem.* **2013**, *125*, 12626; h) Y. Zhou, W. You, K. B. Smith, M. K. Brown, *Angew. Chem. Int. Ed.* **2014**, *53*, 3475; *Angew. Chem.* **2014**, *126*, 3543; i) K. Semba, Y. Nakao, *J. Am. Chem. Soc.* **2014**, *136*, 7567; j) Y. Yang, S. L. Buchwald, *Angew. Chem. Int. Ed.* **2014**, *53*, 8677; *Angew. Chem.* **2014**, *126*, 8821; see the Supporting Information for a complete list of references.

[6] a) H. Noguchi, K. Hojo, M. Suginome, *J. Am. Chem. Soc.* **2007**, *129*, 758; b) N. Iwadate, M. Suginome, *Org. Lett.* **2009**, *11*, 1899; c) N. Iwadate, M. Suginome, *J. Am. Chem. Soc.* **2010**, *132*, 2548.

[7] J. L. Wood, L. D. Marciasini, M. Vaultier, M. Pucheault, *Synlett* **2014**, 551.

[8] a) S. Jaime-Figueroa, Y. Liu, J. M. Muchowski, D. G. Putman, *Tetrahedron Lett.* **1998**, *39*, 1313; b) V. Cadierno, S. E. García-Garrido, J. Gimeno, N. Nebra, *Chem. Commun.* **2005**, 4086; c) J.-Y. Wang, D.-X. Wang, Q.-Y. Zheng, Z.-T. Huang, M.-X. Wang, *J. Org. Chem.* **2007**, *72*, 2040.

[9] a) M. Noack, R. Göttlich, *Chem. Commun.* **2002**, 536; see also: b) T. Tsuritani, H. Shinokubo, K. Oshima, *Org. Lett.* **2001**, *3*, 2709; c) T. Tsuritani, H. Shinokubo, K. Oshima, *J. Org. Chem.* **2003**, *68*, 3246.

[10] Very recently, the copper-catalyzed hydroboration of terminal alkynes with pinB–Bdan was reported; the Bdan group was selectively incorporated; see: H. Yoshida, Y. Takemoto, K. Takaki, *Chem. Commun.* **2014**, *50*, 8299.

[11] a) K. S. Webb, D. Levy, *Tetrahedron Lett.* **1995**, *36*, 5117; b) R. E. Maleczka, Jr., F. Shi, D. Holmes, M. R. Smith III, *J. Am. Chem. Soc.* **2003**, *125*, 7792.

[12] J. Zhou, J. F. Hartwig, *J. Am. Chem. Soc.* **2008**, *130*, 12220.

[13] The enantiomeric ratio was determined by HPLC analysis on a chiral stationary phase; see the Supporting Information for details, including information on the assignment of the absolute configuration.

[14] a) T. Tsuda, T. Hashimoto, T. Saegusa, *J. Am. Chem. Soc.* **1972**, *94*, 658; b) T. H. Lemmen, G. V. Goeden, J. C. Huffman, R. L. Geerts, K. G. Caulton, *Inorg. Chem.* **1990**, *29*, 3680.

[15] D. S. Laitar, P. Müller, J. P. Sadighi, *J. Am. Chem. Soc.* **2005**, *127*, 17196.

[16] D. S. Laitar, E. Y. Tsui, J. P. Sadighi, *Organometallics* **2006**, *25*, 2405.

[17] a) T. Ohishi, M. Nishiura, Z. Hou, *Angew. Chem. Int. Ed.* **2008**, *47*, 5792; *Angew. Chem.* **2008**, *120*, 5876; b) T. Ohishi, L. Zhang, M. Nishiura, Z. Hou, *Angew. Chem. Int. Ed.* **2011**, *50*, 8114; *Angew. Chem.* **2011**, *123*, 8264.

