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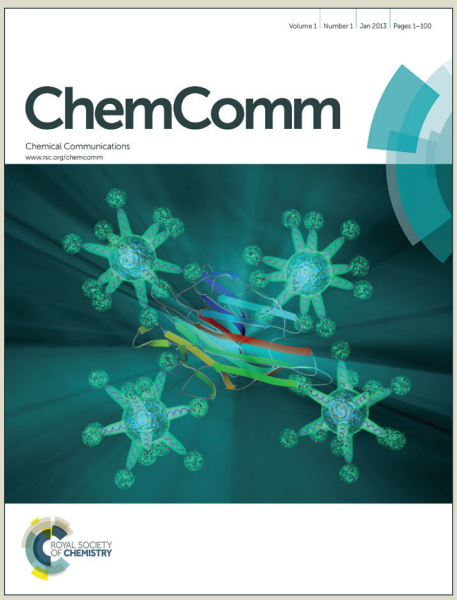

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ARTICLE TYPE

Direct Cross Coupling of Benzyl Alcohols to Construct Diarylmethanes *via* Palladium Catalysis

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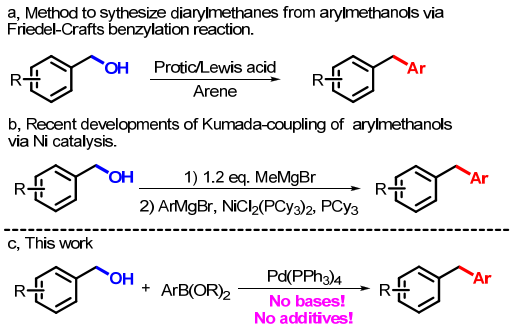
Direct arylation to furnish diarylmethanes from benzyl alcohols was realized through $Pd(PPh_3)_4$-catalyzed Suzuki-Miyaura coupling via benzylic C-O activation in the absence of any additives. The arylation is compatible with various functional groups. This development provides an atom- and step- economic way to approach diarylmethane scaffold under mild and environmentally benign conditions.

Diarymethane is an important structural motif in supramolecules[1] and pharmaceuticals.[2] Conventionally they are prepared by electrophilic aromatic substitution with carbon electrophiles (Friedel–Crafts benzylation).[3] This method showed great power while to some extents the disadvantages, such as low regio-selectivity and requirement of large amounts of acids/Lewis acids, hampered its applications (scheme 1a). Recent development of transition metal-catalyzed cross-coupling has been one of the most powerful tools to achieve such a goal since 1970s.[4] However, at this stage, the use of benzyl halides and their equivalents[5] limited its application due to the sluggish preparation and undesirable byproducts. Recently, more readily available and environmentally benign chemicals, such as benzylic carboxylates,[6] ethers,[7] and other derivatives of benzyl alcohol[5a,5b,8] have been successfully applied in cross couplings to partially solve this problem.

In comparison, alcohol is one of the most abundant organic compounds in nature and synthetic world. However, direct application of alcohols in cross coupling to construct carbon-carbon bonds is rarely touched, although it exhibited the great step-, redox- as well as atom- economy. To the best of our knowledge, only relatively active allylic,[9] propargylic,[10] and allenylic alcohols[11] have been directly applied as the electrophiles in cross couplings up to date. As one of broadly existing alcohols, benzyl alcohols have never been directly used as coupling partner until the only example of direct cross-coupling of benzylic alcohol catalyzed by nickel catalyst with using excess Grignard reagents (Scheme 1b).[12] Due to the high reactivity of Grignard reagents as partners, the poor functional group tolerance highly limited the potential applications. According to the importance of diarylmethane scaffolds, we conceived that direct arylation of benzyl alcohols through cross coupling with other stable organometallic reagents. Therein, we reported direct Suzuki-Miyaura coupling of benzylic alcohols with $Pd(PPh_3)_4$ as catalyst in the absence of any bases or additives (Scheme 1c).

We initiated our studies based on the reported arylation of naphtholates with aryl boroxines via potential "mutual activation".[13] However the test of the same conditions as the cross coupling of naphtholates into the desired coupling completely failed (eq. 1). To our delight, if sodium carbonate was used as the base in the absence of other additives, the cross coupling of 2-naphthylmethanol **1a** with phenylboroxine **2a** took place and the desired product **1ac** was obtained in the presence of $Ni(COD)_2$ and PCy_3 as catalysts, albeit in a low yield. Different parameters of the reaction conditions were tested and we found that the highest GC yield of 60% of **1ac** was reached (eq. 2). Unfortunately, any other trials we have done could not promote the efficiency, thus we had to give up such a catalytic system. Therefore we turned out to search for the Pd catalytic system to precede such a desirable arylation reaction.

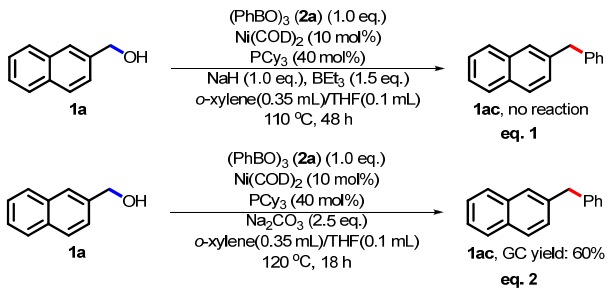
Scheme 1. Design of direct cross coupling of benzyl alcohols with arylboronic acid derivatives.



In this context, we also conceived that the Lewis acidity of boronic acid derivatives and the Lewis basicity of benzyl alcohol themselves might be strong enough to activate each other by the formation of the borates (or their interaction strong enough) to facilitate the desired cross coupling. Based on this assumption, we first tested the interaction between naphthylmethanol **1a** and phenylboroxine **2a**. We compared the ^1H and ^{13}C NMR of naphthylmethanol, phenylboroxine and the mixture of these two compounds in d^8-THF (Figure 1). To our interest, the very clean NMR spectroscopy indicated that, both chemical shift of ^1H NMR and ^{13}C NMR signal of benzylic-CH_2 moved downfield in the presence of the phenylboroxine. These data strongly support the interaction between naphthylmethanol and Lewis acidic phenylboroxine (details refers to supporting information). With the additional

reactivity investigation of boranes-alcohol complex (eq. 3) and HRMS studies, we ruled out the formation of benzylboronic ester and confirmed the activation of C-O bond via intermolecular coordination.

Scheme 2. Nickel-catalyzed Suzuki-Miyaura coupling based on mutual activation.



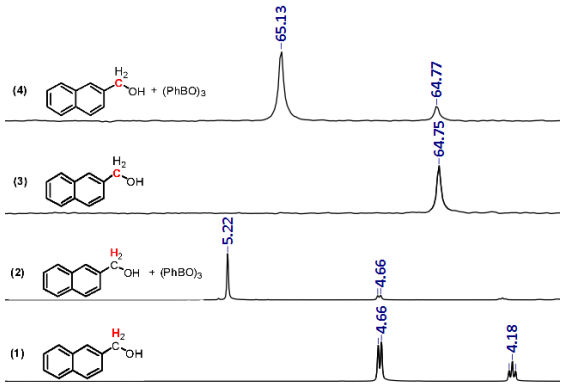
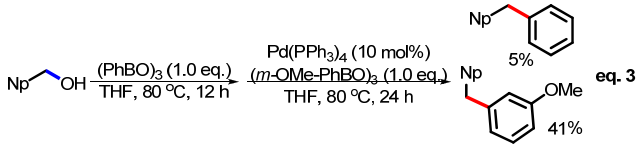


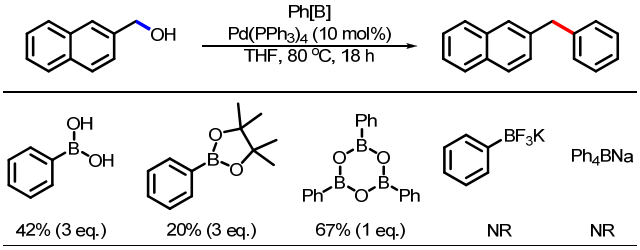
Figure 1. ^{1}H NMR spectra: (1) 2-naphthalenemethanol, δ = 4.66 ppm; (2) 2-naphthalenemethanol + phenylboroxine, δ = 4.66 and 5.22 ppm; ^{13}C NMR spectra: (3) 2-naphthalenemethanol, δ = 64.8 ppm; (4) 2-naphthalenemethanol + phenylboroxine, δ = 64.8 and 65.1 ppm.



To our interest, the cross coupling between naphthylmethanol and phenylboronic acid only in the presence of catalytic $Pd(PPh_3)_4$ with THF as solvent gave the desired product **3a** in 42% NMR yield (Table 1). Stimulated by this result, we further tested the different derivatives of phenylboronic acid. The phenylboroxine showed the best reactivity to produce the desired product in 67% NMR yield while the corresponding phenylboronic ester gave a poor yield. Obviously, the prepared borates, such as potassium phenyl trifluoroborate and sodium tetraphenylborate, failed in this cross coupling by losing the Lewis acidity of boron atom, further supporting our suspension.

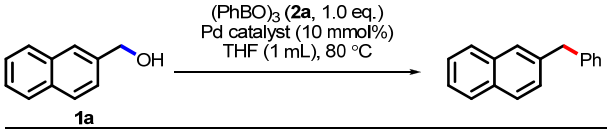
Based on this observation, we screened different parameters of the reaction conditions (Table 2). We systematically examined the influences of different kinds of palladium catalysts, solvents, temperature, catalyst loading and reaction time with **1a** and **2a** as the model substrates. Among the palladium catalysts that were screened, $Pd(PPh_3)_4$ was proved to be the most efficient, giving the desired product **1ac** in 67% isolated yield (Entry 1). Additionally, we considered to generate $Pd(PPh_3)_4$ *in-situ* from other kinds of palladium catalysts and the corresponding

Table 1. Screening of phenylboronic acid derivatives.[a,b]



[a] All reactions were carried out on a 0.2 mmol scale with 10 mol % $Pd(PPh_3)_4$ in THF (1 mL); [b] yield determined by ^{1}H NMR spectroscopy using anisole as an internal standard.

Table 2. Exploration of reaction conditions to carry out arylation of 2-naphthylmethanol.[a]



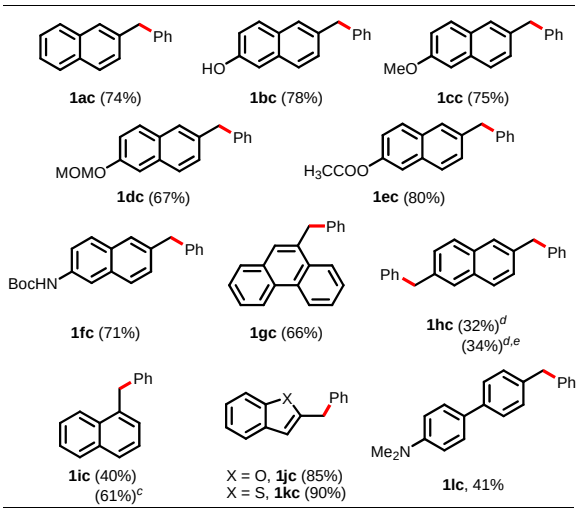
Entry	cat (10 mol%)	t (h)	Y (%)
1	$Pd(PPh_3)_4$	18	67
2	$Pd(OAc)_2$ + PPh_3 (40%)	18	47
3	$PdCl_2$ + PPh_3 (40%)	18	NP
4	$Pd(tfa)_2$ + PPh_3 (40%)	18	23
5	$[PdCl(C_3H_5)]_2$ + PPh_3 (40%)	18	NP
6	$Pd(dba)_2$ + PPh_3 (40%)	18	NP
7	K_2PdCl_4 + PPh_3 (40%)	18	NP
8	$Pd(OAc)_2$ + $(p\text{-Me-}C_6H_4)_3P$ (40%)	18	62
9	$Pd(OAc)_2$ + $(p\text{-F-}C_6H_4)_3P$ (40%)	18	trace
10	$Pd(OAc)_2$ + $(p\text{-MeO-}C_6H_4)_3P$ (40%)	18	37
11	$Pd(OAc)_2$ + PCy_3 (40%)	18	NP
12[c]	$Pd(PPh_3)_4$	18	45
13[d]	$Pd(PPh_3)_4$	18	trace
14[e]	$Pd(PPh_3)_4$	18	49
15[f]	$Pd(PPh_3)_4$	18	trace
16[g]	$Pd(PPh_3)_4$	18	NP
17[h]	$Pd(PPh_3)_4$	18	NP
18	$Pd(PPh_3)_4$	24	82, 74[i]
19[j]	$Pd(PPh_3)_4$	24	50
20[k]	$Pd(PPh_3)_4$	24	74

[a] all reactions were carried out on a 0.2 mmol scale. [b] yield determind by ^{1}H NMR spectroscopy using anisole as an internal standard. [c] 5 mol% Pd catalyst. [d] 1 mol% Pd catalyst. [e] 1, 4-dioxane was used as solvent [f] toluene was used as solvent. [g] methanol was used as solvent. [h] DMF was used as solvent. [i] isolated yield. [j] the reaction were run at 70 °C. [k] the reaction run at 90 °C

ligands. To our disappointment, only $Pd(OAc)_2$ and $Pd(TFA)_2$ afforded the desired product while in lower yields (Entries 2 and 4). Particularly, when $Pd(dba)_2$ or K_2PdCl_4 (Entries 3, 5, 6 and 7) were used, no desired product was obtained at all. The combination of $Pd(OAc)_2$ and other more electron-rich phosphines also failed (Entries 8, 9, 10 and 11). The investigation of catalyst loading indicated that the concentration of catalyst was very important for the reaction. The yield decreased dramatically when the catalyst loading was reduced. For example, only a trace amount of desired product was achieved when 1 mol% $Pd(PPh_3)_4$ was used (Entry 9). As we expected, solvents also played a significant role in this transformation. Compared to non-polar toluene, polar DMF, and protic solvent methanol (Entries 15, 16 and

17), etheric solvents were more effective (Entries 1 and 14), probably arising from the stabilization of the intermediate by weak interaction. Notably, an accurate control of temperature is critical and highest yield was obtained at 80 °C (Entries 18, 19 and 20). The influence of time was also investigated and it was found that the reaction gave a complete conversion in 24 h (Entry 18).

Table 3. Scope of various benzylic alcohols.[a,b]

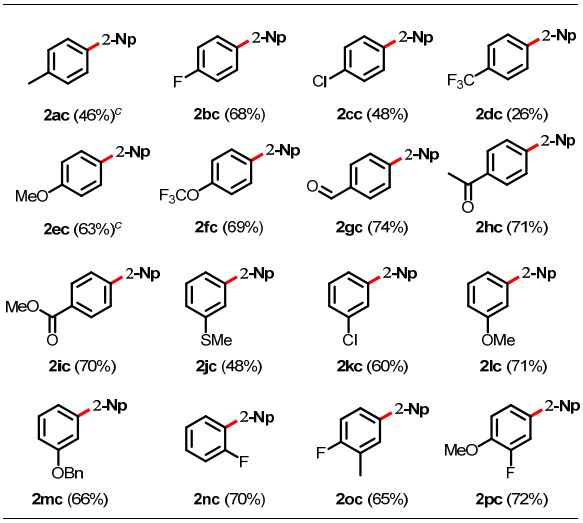


[a] All reactions were carried out on a 0.2 mmol scale with 10 mol% $Pd(PPh_3)_4$ in THF (1 mL); [b] Isolated yield; [c] 1.2 equiv. $(PhBO)_3$; [d] 2.0 equiv. $(PhBO)_3$; [e] 20 mol% $Pd(PPh_3)_4$

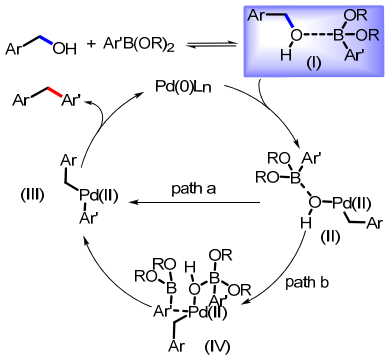
With the optimized conditions in hand, we tested a variety of arylmethanols (Table 3). We found that, various reactive functional groups survived very well under the standard conditions, such as ether (**1cc**), acetal (**1dc**) and ester (**1ec**), which can undergo subsequential transformation via transition-metal catalysis.[14] It is noteworthy that phenolic hydroxyl group was tolerated in this catalytic system and the synthesis of product (**1bc**) was first reported via cross-coupling, which can be further coupled with different organometallic reagents *via* Ni catalysis.[13,15] Products (**1hc**) and (**1ic**) can be furnished in synthetically useful yields, although with a little variation from the standard conditions. This methodology was also applied to fused ring (**1gc**) and heterocycles (**1jc** and **1kc**). We also investigated the simple benzylic alcohols in this system. Product 4'-benzyl-*N*,*N*-dimethylbiphenyl-4-amine (**1lc**) can be obtained albeit in lower yield, which is concord with the precedent works.[7e,16]

Further investigation also indicated that the broad scope of boroxines highly expanded its application (Table 4). Substituted arylboroxines, such as *para*-, *meta*-, *ortho*-substituted boroxines, are suitable, offering the desired diarylmethane derivatives in moderate to good yields. Both electron-rich and electron-deficient arylboroxines were suitable nucleophiles while electron-rich ones need harsher conditions to give satisfactory yields (**2ac**, **2cc** and **2ec**). Notably, the strong electron-withdrawing group dramatically decreased the yield (**2dc**). It is important to note that $C(sp^2)$-Cl and $C(sp^2)$-S bond survived, providing the opportunity to furnish more complex compounds by orthogonal cross-coupling.[17] For the multi-substituted phenylboroxines, the desired diarylmethane derivatives also can be furnished in high yields with predictable selectivity, thus providing a supplemental method to construct complicated diarylmethanes toward the Friedel-Craft reaction (**2oc** and **2pc**).

Table 4. Scope of arylboroxines.[a,b]



[a] All reactions were carried out on a 0.2 mmol scale with 10 mol % $Pd(PPh_3)_4$ in THF (1 mL); [b] Isolated yield; [c] 2.0 equiv. $(PhBO)_3$ and 130 °C.



Scheme 3. Proposed mechanism

We proposed the catalytic cycle as scheme 3. Benzylic alcohols **1a** reacted with the phenylboroxine **2a** to form the key intermediate (I), which has two important effects to facilitate the cross coupling: Firstly, coordination of boranes-alcohols weakened the benzylic C-O bond in benzylic alcohols. Secondly, the alcohols act as an inner-base to activate the C-B bond. I subsequently underwent oxidative addition to Pd(0) to generate the Pd(II) species (II), which further proceeded the intramolecular (path a) or intermolecular (path b) transmetallation to form key intermediate (III). The reductive elimination of (III) gave the desired product **1ac** to fulfill the catalytic cycle by regenerating the active catalytic Pd(0) species.

In summary, we for the first time developed a simple and efficient cross-coupling of benzylic alcohol with arylboronic acid derivatives through Pd-catalyzed C-O bond activation. Such a transformation is atom- and step- economic to construct diarylmethanes from benzyl alcohols in the absence of any additives and bases under mild conditions. This method is a privileged alternative to build up diarylmethane scaffold, thereby complementing earlier catalytic methods typically from benzyl halides and benzylic alcohol derivatives and Friedel-Crafts

benzylation. Further investigations to expend the substrate scope, to promote the efficiency and detailed mechanism are underway.

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Notes and References

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† *Electronic Supplementary Information (ESI) available: [details of any supplementary information available should be included here]. See DOI: 10.1039/b000000x/*

1 (a) M. M. Conn and J. Rebek, *Chem. Rev.*, 1997, **97**, 1647; (b) A. Jasat and J. C. Sherman, *Chem. Rev.*, 1999, **99**, 931.

2 (a) A. Gangjee, R. Devraj and S. F. Queener, *J. Med. Chem.* 1997, **40**, 470; (b) Y.-Q. Long, X.-H. Jiang, R. Dayam, T. Sachez, R. Shoemaker, S. Sei and N. Neamati, *J. Med. Chem.* 2004, **47**, 2561; (c) A. V. Cheltsov, M. Aoyagi, A. Aleshin, E. C.-W. Yu, T. Gilliland, D. Zhai, A. A. Bobkov, J. C. Reed, R. C. Liddington and R. Abagyan, *J. Med. Chem.* 2010, **53**, 3899; (d) W. J. Moree, B.-F. Li, F. Jovic, T. Coon, J. Yu, R. S. Gross, F. Tucci, D. Marinkovic, S. Zamani-Kord, S. Malany, M. J. Bradbury, L. M. Hernandez, Z. O'Brien, J. Wen, H. Wang, S. R. J. Hoare, R. E. Petroski, A. Sacaan, A. Madan, P. D. Crowe and G. Beaton, *J. Med. Chem.* 2009, **52**, 5307.

3 (a) G. A. Olah, S. Kobayashi and M. Tashiro, *J. Am. Chem. Soc.*, 1972, **94**, 7448-7461; (b) M. Rueping and B. J. Nachtsheim, *Beilstein Journal of Organic Chemistry*, 2010, **6**, 6.

4 (a) R. F. Heck and J. P. Nolley, *J. Org. Chem.*, 1972, **37**, 2320; (b) E. Negishi, A. O. King and N. Okukado, *J. Org. Chem.*, 1977, **42**, 1821; (c) J. K. Stille, *Angew. Chem. Int. Ed. Engl.*, 1986, **25**, 508; (d) J. Tsuji, J. Chemiker and J. Chemist, *Palladium reagents and catalysts: innovations in organic synthesis*, Wiley & sons Chichester, UK, 1995; (e) J. Hassan, M. Sévignon, C. Gozzi, E. Schulz and M. Lemaire, *Chem. Rev.*, 2002, **102**, 1359; (f) E.-i. Negishi and A. de Meijere, *Handbook of organopalladium chemistry for organic synthesis*, Wiley-Interscience New York, 2002; (g) L. Jiang, S. Buchwald, A. De Meijere and F. Diederich, *For a review of C–N cross-coupling reaction A. Meijere, F. Diederich (Eds.) Wiley-VCH, Weinheim*, 2004, 699; (h) F. Diederich and P. J. Stang, *Metal-catalyzed cross-coupling reactions*, John Wiley & Sons, 2008; (i) J. F. Hartwig, *Organotransition metal chemistry: from bonding to catalysis*, Univ Science Books, 2010.

5 (a) M. McLaughlin, *Org. Lett.*, 2005, **7**, 4875; (b) C. C. Kofink and P. Knochel, *Org. Lett.*, 2006, **8**, 4121; (c) B. Liegault, J.-L. Renaud and C. Bruneau, *Chem. Soc. Rev.*, 2008, **37**, 290; and references therein.

6 (a) J.-Y. Legros and J.-C. Fiaud, *Tetrahedron Lett.*, 1992, **33**, 2509; (b) J.-Y. Legros, M. Toffano and J.-C. Fiaud, *Tetrahedron*, 1995, **51**, 3235; (c) A. Boutros, J.-Y. Legros and J.-C. Fiaud, *Tetrahedron Lett.*, 1999, **40**, 7329; (d) J.-Y. Legros, G. Primault, M. Toffano, M.-A. Rivière and J.-C. Fiaud, *Org. Lett.*, 2000, **2**, 433; (e) R. Kuwano, Y. Kondo and Y. Matsuyama, *J. Am. Chem. Soc.*, 2003, **125**, 12104; (f) R. Kuwano and M. Yokogi, *Org. Lett.*, 2005, **7**, 945; (g) R. Kuwano and M. Yokogi, *Chem. Commun.*, 2005, 5899; (h) H. Narahashi, I. Shimizu and A. Yamamoto, *J. Organomet. Chem.*, 2008, **693**, 283; (i) A. Correa, T. León and R. Martin, *J. Am. Chem. Soc.*, 2013, **136**, 1062; (j) H. M. Wisniewska, E. C. Swift and E. R. Jarvo, *J. Am. Chem. Soc.*, 2013, **135**, 9083; (k) Q. Zhou, H. D. Srinivas, S. Dasgupta and M. P. Watson, *J. Am. Chem. Soc.*, 2013, **135**, 3307; (l) A. Correa and R. Martin, *J. Am. Chem. Soc.*, 2014, **136**, 7253; (m) C. Zarate and R. Martin, *J. Am. Chem. Soc.*, 2014, **136**, 2236.

7 (a) B.-T. Guan, S.-K. Xiang, B.-Q. Wang, Z.-P. Sun, Y. Wang, K.-Q. Zhao and Z.-J. Shi, *J. Am. Chem. Soc.*, 2008, **130**, 3268; (b) B. L. H. Taylor, E. C. Swift, J. D. Waetzig and E. R. Jarvo, *J. Am. Chem. Soc.*, 2010, **133**, 389; (c) M. R. Harris, M. O. Konev and E. R. Jarvo, *J. Am. Chem. Soc.*, 2014, **136**, 7825; (d) I. M. Yonova, A. G. Johnson, C. A. Osborne, C. E. Moore, N. S. Morrissette and E. R. Jarvo, *Angew. Chem. Int. Ed.*, 2014, **53**, 2422; (e) J. Cornella, C. Zarate and R. Martin, *Chem. Soc. Rev.*, 2014, **43**, 8081.

8 (a) R. Kuwano and M. Yokogi, *Org. Lett.*, 2005, **7**, 945; (b) G. A. Molander and M. D. Elia, *J. Org. Chem.*, 2006, **71**, 9198; (c) Y. Nakao, S. Ebata, J. Chen, H. Imanaka and T. Hiyama, *Chem. Lett.*, 2007, **36**, 606; (d) L. Ackermann, S. Barfüsser and J. Pospech, *Org. Lett.*, 2010, **12**, 724; (e) T. Mukai, K. Hirano, T. Satoh and M. Miura, *Org. Lett.*, 2010, **12**, 1360; (f) M. R. Harris, L. E. Hanna, M. A. Greene, C. E. Moore and E. R. Jarvo, *J. Am. Chem. Soc.*, 2013, **135**, 3303; (g) R. Kumar and E. V. Van der Eycken, *Chem. Soc. Rev.*, 2013, **42**, 1121.

9 (a) C. Chuit, H. Felkin, C. Frajerman, G. Roussi and G. Swierczewski, *Chemical Communications (London)*, 1968, 1604; (b) D. E. Bergbreiter and D. A. Weatherford, *J. Chem. Soc., Chem. Commun.*, 1989, 883; (c) M. Kimura, Y. Horino, R. Mukai, S. Tanaka and Y. Tamaru, *J. Am. Chem. Soc.*, 2001, **123**, 10401; (d) Y. Kayaki, T. Koda and T. Ikariya, *Eur. J. Org. Chem.*, 2004, **2004**, 4989; (e) B. M. Trost and J. Quancard, *J. Am. Chem. Soc.*, 2006, **128**, 6314; (f) Y.-X. Li, Q.-Q. Xuan, L. Liu, D. Wang, Y.-J. Chen and C.-J. Li, *J. Am. Chem. Soc.*, 2013, **135**, 12536; (g) J. Ye, J. Zhao, J. Xu, Y. Mao and Y. J. Zhang, *Chem. Commun.*, 2013, **49**, 9761; (h) H.-B. Wu, X.-T. Ma and S.-K. Tian, *Chem. Commun.*, 2014, **50**, 219.

10 Y. Nishibayashi, I. Wakiji and M. Hidai, *J. Am. Chem. Soc.*, 2000, **122**, 11019.

11 M. Yoshida, T. Gotou and M. Ihara, *Chem. Commun.*, 2004, 1124.

12 D.-G. Yu, X. Wang, R.-Y. Zhu, S. Luo, X.-B. Zhang, B.-Q. Wang, L. Wang and Z.-J. Shi, *J. Am. Chem. Soc.*, 2012, **134**, 14638.

13 D.-G. Yu and Z.-J. Shi, *Angew. Chem. Int. Ed.*, 2011, **50**, 7097.

14 (a) J. W. Dankwardt, *Angew. Chem. Int. Ed.*, 2004, **43**, 2428; (b) K. W. Quasdorf, X. Tian and N. K. Garg, *J. Am. Chem. Soc.*, 2008, **130**, 14422; (c) B.-T. Guan, Y. Wang, B.-J. Li, D.-G. Yu and Z.-J. Shi, *J. Am. Chem. Soc.*, 2008, **130**, 14468; (d) B.-T. Guan, S.-K. Xiang, T. Wu, Z.-P. Sun, B.-Q. Wang, K.-Q. Zhao and Z.-J. Shi, *Chem. Commun.*, 2008, 1437; (e) M. Tobisu, T. Shimasaki and N. Chatani, *Angew. Chem. Int. Ed.*, 2008, **47**, 4866; (f) P. Álvarez-Bercedo and R. Martin, *J. Am. Chem. Soc.*, 2010, **132**, 17352; (g) K. Muto, J. Yamaguchi and K. Itami, *J. Am. Chem. Soc.*, 2011, **134**, 169; (h) C. Wang, T. Ozaki, R. Takita and M. Uchiyama, *Chem. – Eur. J.*, 2012, **18**, 3482; (i) L. Meng, Y. Kamada, K. Muto, J. Yamaguchi and K. Itami, *Angew. Chem. Int. Ed.*, 2013, **52**, 10048; (j) R. Takise, K. Muto, J. Yamaguchi and K. Itami, *Angew. Chem. Int. Ed.*, 2014, **53**, 6791; (k) A. Correa and R. Martin, *J. Am. Chem. Soc.*, 2014, **136**, 7253.

15 D.-G. Yu, B.-J. Li, S.-F. Zheng, B.-T. Guan, B.-Q. Wang and Z.-J. Shi, *Angew. Chem. Int. Ed.*, 2010, **49**, 4566.

16 J. Cornella, E. Gómez-Bengoa and R. Martin, *J. Am. Chem. Soc.*, 2013, **135**, 1997.

17 (a) S. G. Murray and F. R. Hartley, *Chem. Rev.*, 1981, **81**, 365; (b) N. Miyaura and A. Suzuki, *Chem. Rev.*, 1995, **95**, 2457; (c) R. Martin and S. L. Buchwald, *Acc. Chem. Res.*, 2008, **41**, 1461; (d) N. Barbero and R. Martin, *Org. Lett.*, 2012, **14**, 796; (e) F. Pan, H. Wang, P.-X. Shen, J. Zhao and Z.-J. Shi, *Chem. Sci.*, 2013, **4**, 1573; (f) J. F. Hooper, R. D. Young, I. Pernik, A. S. Weller and M. C. Willis, *Chem. Sci.*, 2013, **4**, 1568.