SCIENCE CHINA
Chemistry

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https://doi.org/10.1007/s11426-018-9344-4

Base-catalyzed diborylation of alkynes: synthesis and applications of *cis*-1,2-bis(boryl)alkenes

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Received June 3, 2018; accepted August 1, 2018; published online September 14, 2018

An efficient, transition-metal free, and practical approach to *cis*-bis(boryl)alkenes from various alkynes was disclosed in the presence of a catalytic amount of K_2CO_3 under mild conditions. Meanwhile, tetrasubstituted alkenes and phenanthrene derivatives were readily constructed from the target diborylalkenes via Suzuki-Miyaura cross coupling.

base-catalyzed, diborylation of alkynes, *cis*-1,2-bis(boryl)alkenes

Citation: Kuang Z, Gao G, Song Q. Base-catalyzed diborylation of alkynes: synthesis and applications of *cis*-1,2-bis(boryl)alkenes. *Sci China Chem*, 2018, 61, https://doi.org/10.1007/s11426-018-9344-4

With the development of Suzuki-Miyaura cross-coupling reactions, alkenylboron compounds have gained great interests as key intermediates for the synthesis of diverse functional molecules as electronic materials [1] and bioactive natural products [2]. Diborylalkenes are particularly attractive building blocks for multi-substituted alkenes [3] and π-extended polyarenes [4], and their expedient synthesis has attracted much attention from synthetic chemists. A number of transition metals, such as cobalt, copper [5], iridium [6], gold [7], iron [8], platinum [9], cobalt [10a] and palladium [10b,10c] have been utilized in both homogenous and heterogenous catalytic additions of B–B bonds (e.g., diboration) to alkynes rendering *cis*-bis(boryl)alkenes (Scheme 1(a)). Among them, platinum is by far the most effective and widely studied, which is attributed to the facile cleavage of the B–B bond and the lability of the corresponding bis(boryl)platinum complexes [9]. Although these metal-catalyzed approaches to *cis*-bis(boryl)alkenes proceed successfully, a metal-free diboration [11] process has long been desired, partially because these boron compounds are intermediates for the preparation of drugs and electronic materials where a heavy metal can be a vital problem. In recent years, organocatalytic protocols have also been developed, examples include PBu_3 [12a], $(PhS)_2$ [12b], and PPh_3 [12c], however, *trans*-bis(boryl)alkenes instead of the *cis* ones were afforded (Scheme 1(b)). To our knowledge, a transition-metal-free version of diboration (B_2pin_2) of alkynes leading to 1,2-diborylalkenes has not been well studies and the rare elegant examples [13] for theses also covered the *trans*-diboration of propargylic alcohols with stoichiometric amount of *n*-BuLi (Scheme 1(c)), which is air- and moisture-sensitive and has strong nucleophilicity, such caused a limited functional group tolerance. Herein, we report an efficient and convenient approach to *cis*-bis(boryl)alkenes through a catalytic amount of K_2CO_3 catalyzed reaction between various alkynes and B_2pin_2 (Scheme 1(d)). The simple, mild and transition-metal-free reaction conditions as well as cheap and readily available K_2CO_3 as catalyst are attractive features for this protocol.

Based on our previous studies on domino-borylation-protodeboronation (DBP) [14] strategy and base-promoted B–B

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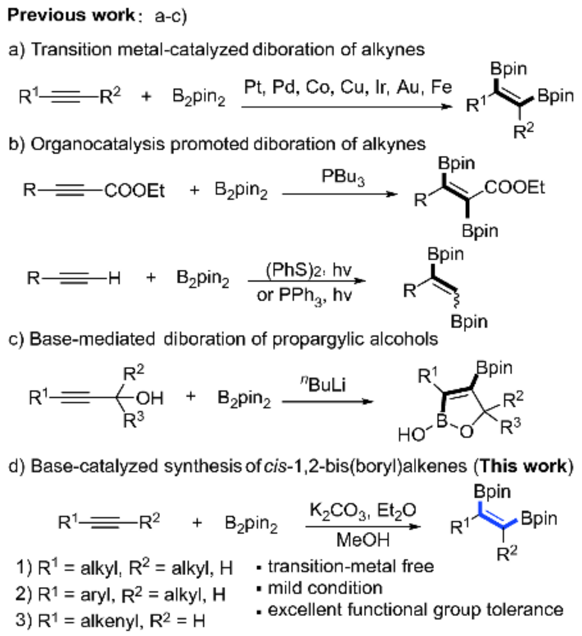
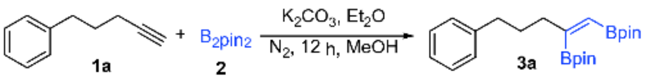


Scheme 1 Synthesis of vinyl 1,2-bis(boronates) (color online).

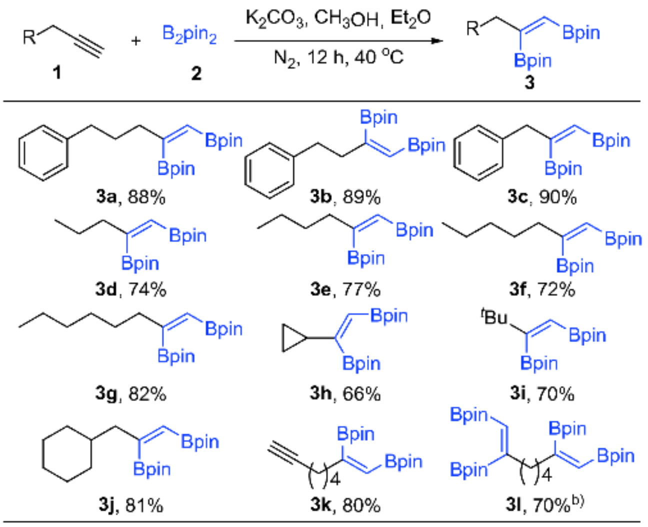
Table 1 Optimization of reaction conditions



Entry	B_2pin_2 (x equiv.)	K_2CO_3 (y equiv.)	Temp. (°C)	Yield (%)[a)]
1	3.0	0.1	50	70
2	3.0	0.2	50	56
3	3.0	0.3	50	32
4	3.0	1.0	50	trace
5	3.0	0.05	50	67
6	3.0	0.08	50	65
7	2.5	0.1	50	44
8	2.0	0.1	50	88
9	1.5	0.1	50	66
10	1.0	0.1	50	62
11	2.0	0.1	rt	70
12	2.0	0.1	40	94(88)[b)]

Conditions: **1a** (0.2 mmol), **2** (x equiv.), K_2CO_3 (y equiv.), Et_2O (1 mL), MeOH (10 equiv.). a) GC yield; b) isolated yield.

Table 2 Synthesis of *cis*-bis(boryl)alkenes from terminal aliphatic alkynes[a)]



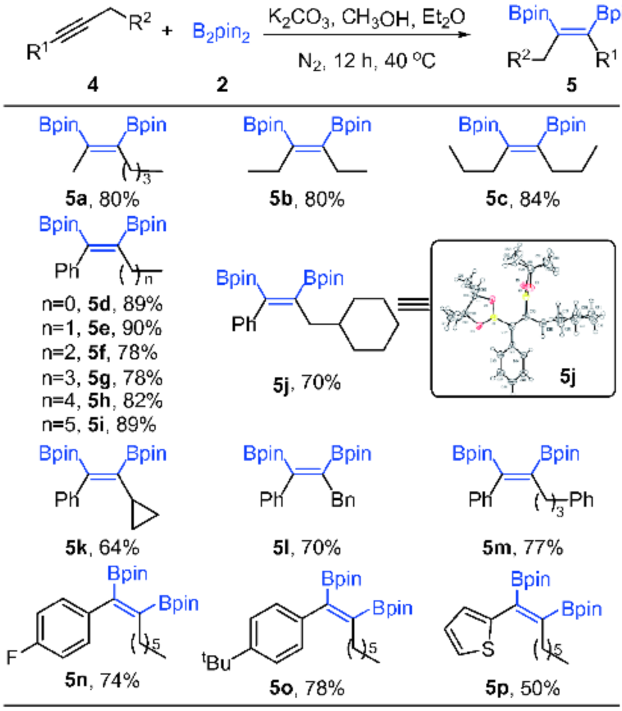
a) Conditions: alkyne **1** (0.2 mmol), B_2pin_2 (**2**) (2 equiv.), K_2CO_3 (0.1 equiv.), Et_2O (1 mL), MeOH (10 equiv.), 12 h, N_2; isolated yield. b) B_2pin_2 (4 equiv.), K_2CO_3 (0.3 equiv.), Et_2O (2 mL).

bond activation and C–B bond formation, we directly screened base catalysts and found that a catalytic amount K_2CO_3 (other bases such as Cs_2CO_3, KO^tBu, K_3PO_4 were also effective) can promote the diboration of alkynes. We commenced our studies by examining the reaction between 5-phenyl-1-pentyne (**1a**) with B_2pin_2 (**2**) under catalytic amount of K_2CO_3 in the presence of MeOH. Further screening delivered 70% of the desired 1,2-diborylalkene (**3a**) when 0.1 equiv. of K_2CO_3 was used as the catalyst with 3 equiv. of B_2pin_2 in Et_2O at 50 °C for 12 h (Table 1, entry 1). It was of note that further increasing (Table 1, entries 2–4) or reducing (Table 1, entries 5, 6) the amount of K_2CO_3 only led to the inferior yields. Of note, stoichiometric amount base would lead to alkyl 1,2-bis(boronates) [11g, 14e] (entry 4). Screening on the amount of B_2pin_2 suggested that 2 equiv. is the best one (Table 1, entries 7–10). To further optimize this condition, the impact of temperature was examined as well (Table 1, entries 11, 12) and it turned out that 40 °C is the optimal one, since alkyl 1,1,2-tris(boronate) [14e] was produced at higher temperatures.

With the optimal conditions in hand (Table 1, entry 12), the substrate scope of terminal aliphatic alkynes were first investigated and the results were shown in Table 2. In addition to **3a**, **3b** and **3c** in which a benzene ring was attached on the end of the linear alkyl chain could be obtained in good yields, we found that a more general terminal alkynes which contain no benzene rings were compatible for this transformation as well and when they were subjected to the standard conditions, good yields were obtained (Table 2, **3d**–**3j**). It is worth mentioning that 1,7-octadiyne could acquire mono-alkyne **3k** under the standard conditions in 80% yield, gratifyingly, when the amount of B_2pin_2 was increased to 4 equiv., **3l**, which contained four boryl moieties was obtained in 70% yield. We noticed the subtlety of the reaction conditions that five times amount of base (0.5 equiv. NaOMe) gave the alkyl 1,2-bis(boronates) at the same temperature [11g], higher temperature (60 °C) and six times amount of base (0.6 equiv. K_2CO_3) yielded the alkyl 1,1,2-tris(boronates) [14e], and the stronger, stoichiometric Cs_2CO_3 led to the alkyl 1,2-bis(boronates) [14e] with the same substrates.

We next investigated the scope of internal alkynes under the optimal conditions and the results were listed in Table 3. As we can see, linear aliphatic internal alkynes were com-

Table 3 Synthesis of *cis*-bis(boryl)alkenes from internal alkynes[a)]

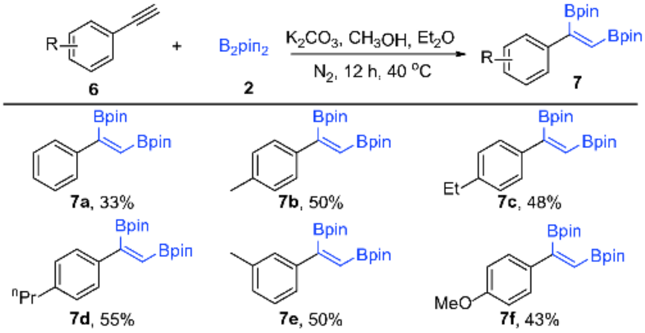


a) Conditions: alkyne **4** (0.2 mmol), B_2pin_2 (**2**) (2 equiv.), K_2CO_3 (0.1 equiv.), Et_2O (1 mL), MeOH (10 equiv.), 12 h, N_2, isolated yields.

patible under the standard conditions, leading to the corresponding *cis*-bis(boryl)alkenes with high chemoselectivity in good to excellent yields (**5a**–**5c**, 80%–84%). The broad substrate scope of alkynes was further demonstrated by the successful reaction of aryl-(alkyl) internal alkynes (**4d**–**4i**) to products **5d**–**5i** (78%–90%), and also by the reaction of **4k**–**4m**, which were sterically hindered around the triple bond yet were all well tolerated in this transformation. Moreover, the structure of vicinal diborylalkene **5j** was unambiguously confirmed by X-ray single crystal analysis. Not surprisingly, 1-phenyl-1-octyne (**4i**) can acquire meritoriously yield (89%), so we intend to change the substituents on the benzene ring to explore the compatibility of the reaction, and the corresponding *cis*-bis(boryl)alkenes were obtained in decent yields (**5n**–**5o**, 74%−78%). Moreover, the heteroaromatic ring was also good candidates and the target molecule was generated in moderate yields (**5p**, 50%). But, when the substrate with strong electron-deficient groups, such as cyano, ketone and ester, the major products were *geminal*-diborylalkanes [14g].

The substrate scope was subsequently explored and broadened by investigating the more specific terminal aryl alkynes (Table 4) (we screened the conditions again in order to gain best results, see Supporting Information online for details). To our delight, this protocol was found to successfully incorporate all above terminal aromatic alkynes into the corresponding diborylalkenes in moderate yields with high regio-selectivities (**7a**–**7f**, 33%–43%). However, the same substrates suffered with the more (0.5 equiv.) and stronger base (NaOMe) to render the mono(boryl)alkenes at same temperature [11g], the alkyl 1,1,2-tris(boronates) [14e] (0.3 equiv. K_2CO_3 at 60 °C) and monoalkylboranes [14f] (4 equiv. Cs_2CO_3 at 70 °C).

Table 4 Synthesis of *cis*-bis(boryl)alkenes from terminal aromatic alkynes[a)]



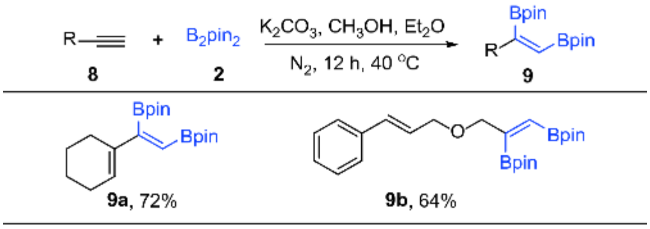
a) Conditions: alkyne **6**(0.2 mmol), B_2pin_2 (**2** equiv.), K_2CO_3 (0.2 equiv.), Et_2O (0.2 mL), MeOH (10 equiv.), 12 h, N_2, isolated yield.

This transformation has excellent chemoselectivity which was demonstrated by employing our conditions to some olefin-containing alkynes even conjugate enyne (**8a**) (Table 5), most remarkably, internal alkene with terminal alkyne **8b** was compatible in this transformation with excellent chemoselectivity.

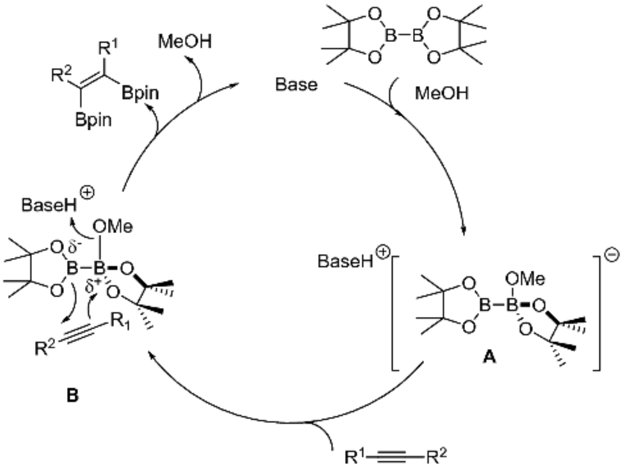
Based our DBP studied [14e–14g] and previous reports [11], we proposed a path to for this transformation depicted in Scheme 2. First, B_2pin_2 is activated in the present of base and MeOH, resulting the $[BaseH]^+\cdot[B_2pin_2\cdot MeO]^-$ **A** *in situ*. Subsequently, the activated and nucleophilic **A** species attacks the C–C triple bond of alkyne, leading to the adduct **B**. Both Bpin moieties attach on the C–C triple bond along with the conjugated acid of the base ($BaseH^+$) and MeO^- to form *cis*-1,2-bis(boryl)alkenes and MeOH and regenerate the base catalyst.

To demonstrate the utility of these transformations, gram-scale reaction was performed under the standard conditions for the formation of *cis*-bis(boryl)alkenes. Treatment of 5 mmol of 1-phenyl-1-butyne (**4e**) with B_2pin_2 afforded the corresponding desired product **5e** in 84% yield (1.62 g) under the optimal conditions (Scheme 3(a)). As we can see, even if the reaction scale was magnified up to 25 times, comparable synthetic valuable yield was still obtained. The utility of *cis*-bis(boryl)alkenes was demonstrated by further extension of compound **5e** into polyaryl olefins **10** [15] and **11b** [4b] via a Suzuki-Miyaura crossing-coupling reaction (Scheme 3(b, c)). Very interestingly yet not surprisingly, when *cis*-bis(boryl)alkene **3a** was exposed under basic conditions (in the presence of 1.5 equiv. of Cs_2CO_3), corresponding 1,2-bis(boronate) **12** [14e] was obtained at 80 °C, which was consistent with our previous research as well as precedent report. Further exposure of compound **3a** to 0.6

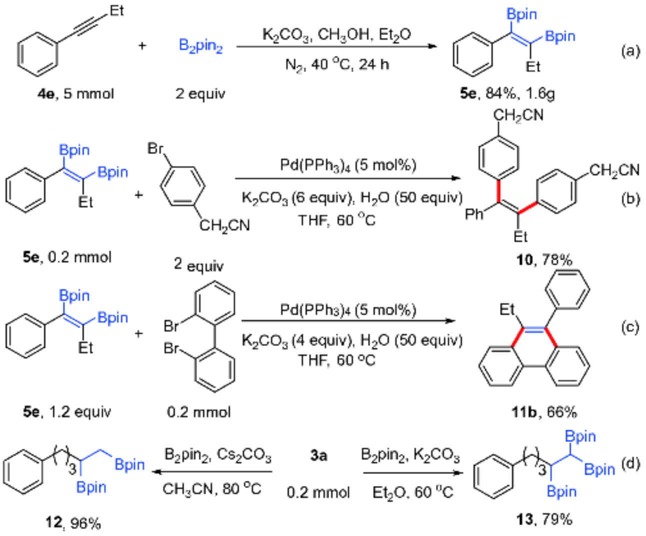
Table 5 Synthesis of *cis*-bis(boryl)alkenes from special C–C double bond-containing alkynes[a)]



a) Conditions: alkyne **8**(0.2 mmol), B_2pin_2 (**2**) (2 equiv.), K_2CO_3 (0.1 equiv.), Et_2O (1 mL), MeOH (10 equiv.), 12 h, N_2, isolated yield.



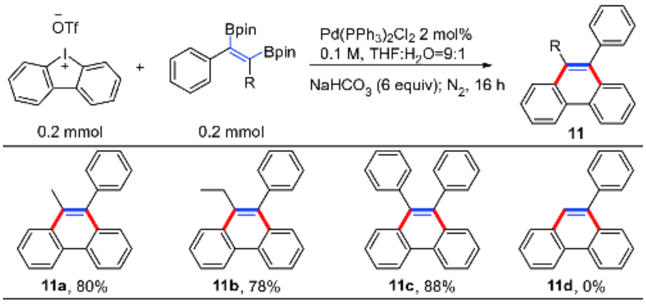
Scheme 2 Proposed mechanism to *cis*-1,2-bis(boryl)alkenes.



Scheme 3 Gram-scale synthesis and transformations of *cis*-bis(boryl)alkenes (color online).

equiv. of K_2CO_3 in Et_2O with MeOH led to alkyl 1,1,2-tris(boronates) **13** [14e] in 79% yield (Scheme 3(d)), which further validates our previous report that *cis*-bis(boryl)alkenes is not stable and Domino-Borylation process will occur under basic conditions under suitable temperature.

Table 6 The construction of phenanthrene derivatives with diaryliodonium salts and diborylalkenes



We envisaged that the target diborylalkenes would react with diaryliodonium salts, which could be considered as a diiodo compounds, by Suzuki-Miyaura cross coupling to give phenanthrene derivatives. Gratifyingly, by brief condition screening, we can get the desired product with excellent yields (see Supporting Information online for details). Subsequent substrate scope for this protocol was carried out. When the substituents R were Me, Et, Ph [16], the transformation could be achieved smoothly to yield target products (**11a**–**11c**) with good yields (Table 6). However, when the diborylalkenes were prepared from terminal alkynes and aliphatic alkynes, the transformation was failed to afford desired product (for example **11d**).

In conclusion, we have developed an efficient and convenient approach for the synthesis of *cis*-bis(boryl)alkenes through a transition-metal-free and base-catalyzed reaction between various alkynes with B_2pin_2 under mild and operational simple strategy. This method furnishes structurally diverse *cis*-bis(boryl)alkenes in good yields and with high chemoselectivity. Thus, the method allows the synthesis of *cis*-bis(boryl)alkenes in a convergent and stereoselective manner from simple precursors under mild conditions and without the use of transition-metal. And the differences between this work and previous work [14e–14g] are the the substrates and the temperature. Importantly, the installed boron substituents of the *cis*-bis(boryl)alkenes could be transformed effectively with Suzuki coupling and rendered tetra-substituted olefins and phenanthrene derivatives which are key scaffolds in many bioactive molecules. At the same time, 1,2-diborylalkanes and 1,1,2-trisborylalkanes could also be readily accessible under our standard basic conditions.

Acknowledgements This work was supported by the National Natural Science Foundation (21772046), Program of Innovative Research Team of Huaqiao University (Z14X0047), the Recruitment Program of Global Experts (1000 Talents Plan), the Natural Science Foundation of Fujian Province (2016J01064) and Postgraduates' Innovative Fund in Scientific Research of Huaqiao University for K. Z. We also thank Instrumental Analysis Center of Huaqiao University.

Conflict of interest The authors declare that they have no conflict of interest.

Supporting information The supporting information is available online at http://chem.scichina.com and http://link.springer.com/journal/11426. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

1 (a) Meier H. *Angew Chem Int Ed Engl*, 1992, 31: 1399–1420; (b) Lo SC, Burn PL. *Chem Rev*, 2007, 107: 1097–1116; (c) Neeve EC, Geier SJ, Mkhalid IAI, Westcott SA, Marder TB. *Chem Rev*, 2016, 116: 9091–9161; (d) Cuenca AB, Shishido R, Ito H, Fernández E. *Chem Soc Rev*, 2017, 46: 415–430

2 (a) Roupe K, Remsberg C, Yanez J, Davies N. *Curr Clin Pharm*, 2006, 1: 81–101; (b) Cottart CH, Nivet-Antoine V, Beaudeux JL. *Mol Nutr Food Res*, 2014, 58: 7–21; (c) Wang C, Wu C, Ge S. *ACS Catal*, 2016, 6: 7585–7589; (d) Xu L, Zhang S, Li P. *Chem Soc Rev*, 2015, 44: 8848–8858

3 (a) Flynn AB, Ogilvie WW. *Chem Rev*, 2007, 107: 4698–4745; (b) Hata T, Kitagawa H, Masai H, Kurahashi T, Shimizu M, Hiyama T. *Angew Chem Int Ed*, 2001, 40: 790–792

4 (a) Faggi E, Sebastian RM, Pleixats R, Vallribera A, Shafir A, Rodriguez-Gimeno A, Ramirez de Arellano C. *J Am Chem Soc*, 2010, 132: 17980–17982; (b) Shimizu M, Nagao I, Tomioka Y, Hiyama T. *Angew Chem Int Ed*, 2008, 47: 8096–8099; (c) Shimizu M, Nagao I, Tomioka Y, Kadowaki T, Hiyama T. *Tetrahedron*, 2011, 67: 8014–8026

5 Yoshida H, Kawashima S, Takemoto Y, Okada K, Ohshita J, Takaki K. *Angew Chem Int Ed*, 2012, 51: 235–238

6 (a) Lee CI, Shih WC, Zhou J, Reibenspies JH, Ozerov OV. *Angew Chem Int Ed*, 2015, 54: 14003–14007; (b) Iwadate N, Suginome M. *J Am Chem Soc*, 2010, 132: 2548–2549

7 (a) Baker RT, Nguyen P, Marder TB, Westcott SA. *Angew Chem Int Ed Engl*, 1995, 34: 1336–1338; (b) Ramírez J, Sanaú M, Fernández E. *Angew Chem Int Ed*, 2008, 47: 5194–5197; (c) Chen Q, Zhao J, Ishikawa Y, Asao N, Yamamoto Y, Jin T. *Org Lett*, 2013, 15: 5766–5769

8 Nakagawa N, Hatakeyama T, Nakamura M. *Chem Eur J*, 2015, 21: 4257–4261

9 (a) Ishiyama T, Matsuda N, Miyaura N, Suzuki A. *J Am Chem Soc*, 1993, 115: 11018–11019; (b) Ishiyama T, Matsuda N, Murata M, Ozawa F, Suzuki A, Miyaura N. *Organometallics*, 1996, 15: 713–720; (c) Lesley G, Nguyen P, Taylor NJ, Marder TB, Scott AJ, Clegg W, Norman NC. *Organometallics*, 1996, 15: 5137–5154; (d) Thomas RL, Souza FES, Marder TB. *J Chem Soc Dalton Trans*, 2001, 30: 1650–1656; (e) Burks HE, Kliman LT, Morken JP. *J Am Chem Soc*, 2009, 131: 9134–9135; (f) Alonso F, Moglie Y, Pastor-Pérez L, Sepúlveda-Escribano A. *ChemCatChem*, 2014, 6: 857–865

10 (a) Adams CJ, Baber RA, Batsanov AS, Bramham G, Charmant JPH, Haddow MF, Howard JAK, Lam WH, Lin Z, Marder TB, Norman NC, Orpen AG. *Dalton Trans*, 2006, 248: 1370–1373; (b) Yang Z, Cao T, Han Y, Lin W, Liu Q, Tang Y, Zhai Y, Jia M, Zhang W, Zhu T, Ma S. *Chin J Chem*, 2017, 35: 1251–1262; (c) Ansell MB, Menezes da Silva VH, Heerdt G, Braga AAC, Spencer J, Navarro O. *Catal Sci Technol*, 2016, 6: 7461–7467

11 (a) Bonet A, Pubill-Ulldemolins C, Bo C, Gulyás H, Fernández E. *Angew Chem Int Ed*, 2011, 50: 7158–7161; (b) Miralles N, Cid J, Cuenca AB, Carbó JJ, Fernández E. *Chem Commun*, 2015, 51: 1693–1696; (c) Cuenca AB, Zigon N, Duplan V, Hoshino M, Fujita M, Fernández E. *Chem Eur J*, 2016, 22: 4723–4726; (d) Bonet A, Sole C, Gulyás H, Fernández E. *Org Biomol Chem*, 2012, 10: 6621–6623e; (e) Blaisdell TP, Caya TC, Zhang L, Sanz-Marco A, Morken JP. *J Am Chem Soc*, 2014, 136: 9264–9267; (f) Miralles N, Alam R, Szabó KJ, Fernández E. *Angew Chem Int Ed*, 2016, 55: 4303–4307; (g) Deng CM, Ma YF, Wen YM. *ChemistrySelect*, 2018, 3: 1202–1204

12 (a) Nagao K, Ohmiya H, Sawamura M. *Org Lett*, 2015, 17: 1304–1307; (b) Yoshimura A, Takamachi Y, Han LB, Ogawa A. *Chem Eur J*, 2015, 21: 13930–13933; (c) Yoshimura A, Takamachi Y, Mihara K, Saeki T, Kawaguchi S, Han LB, Nomoto A, Ogawa A. *Tetrahedron*, 2016, 72: 7832–7838

13 (a) Nagashima Y, Hirano K, Takita R, Uchiyama M. *J Am Chem Soc*, 2014, 136: 8532–8535; (b) Kojima C, Lee KH, Lin Z, Yamashita M. *J Am Chem Soc*, 2016, 138: 6662–6669; (c) Verma A, Snead RF, Dai Y, Slebodnick C, Yang Y, Yu H, Yao F, Santos WL. *Angew Chem Int Ed*, 2017, 56: 5111–5115

14 (a) Feng Q, Yang K, Song Q. *Chem Commun*, 2015, 51: 15394–15397; (b) Ding W, Song Q. *Org Chem Front*, 2016, 3: 14–18; (c) Kuang Z, Li B, Song Q. *Chem Commun*, 2018, 54: 34–37; (d) Xuan Q, Kong W, Song Q. *J Org Chem*, 2017, 82: 7602–7607; (e) Gao G, Yan J, Yang K, Chen F, Song Q. *Green Chem*, 2017, 19: 3997–4001; (f) Yang K, Song Q. *Green Chem*, 2016, 18: 932–936; (g) Gao G, Kuang Z, Song Q. *Org Chem Front*, 2018, 5: 2249–2253

15 Tong S, Xu Z, Mamboury M, Wang Q, Zhu J. *Angew Chem Int Ed*, 2015, 54: 11809–11812

16 The substrate material was synthesized with Ref. [5]