# Scalable, Metal- and Additive-Free, Photoinduced Borylation of Haloarenes and Quaternary Arylammonium Salts

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**S** *Supporting Information*

**ABSTRACT:** We report herein a simple, metal- and additive-free, photoinduced borylation of haloarenes, including electron-rich fluoroarenes, as well as arylammonium salts directly to boronic acids. This borylation method has a broad scope and functional group tolerance. We show that it can be further extended to boronic esters and carried out on gram scale as well as under flow conditions.

Aromatic boronic acids find increasingly important roles in the areas of synthetic organic chemistry,[1] catalysis,[2] molecular self-assembly,[3] carbohydrate analysis,[4] molecular sensing,[5] materials science,[6] and medicinal chemistry.[7] While the reaction of organomagnesium and organolithium reagents with trialkyl borates, first described by Khotinsky (RMgX)[8] and Letsinger (RLi),[9] remains in use, transition-metal-catalyzed C—X[10] and C—H borylation[11] reactions have recently emerged as efficient alternatives that bypass air- and moisture-sensitive intermediates. In addition, transition-metal-free, base-mediated borylation of iodo- and bromoarenes to arylboronic esters[12] as well as the Sandmeyer-type borylation of anilines[13] and electrophilic borylation of electron-rich arenes[14] have been recently developed. These methods can be advantageous, since the use of heavy metals, expensive and air-sensitive catalysts, and ligands can be avoided. However, the practicality and scalability of these methods may be limited by the narrow substrate scope and high molecular weight of the boron reagents.

Photochemical activation of molecules enables reactivity patterns that can be difficult to achieve from the ground states.[15] A multitude of homolytic and heterolytic pathways that can be accessed from singlet and triplet excited states affords numerous synthetic possibilities. A number of photoinduced processes have been successfully adapted in the chemical industry (e.g., the Toray PNC process,[16] rose oxide,[17] and vitamin D[18] syntheses), pointing to the significant potential of photoinduced reactions.[19]

Photoinduced Ar—X bond dissociation is a key step in a number of important photochemical carbon–carbon and carbon–heteroatom bond-forming reactions, including nucleophilic substitution,[20] arylation,[21] alkylation,[22] and photocyclization[23] reactions.

We report herein that haloarenes, including electron-rich fluoroarenes, as well as aryltrimethylammonium salts readily react with tetrahydroxydiboron (first introduced by Molander and Dreher for the Pd- and later Ni-catalyzed borylations)[24] and other diboron reagents to give aromatic boronic acids and esters under ultraviolet light in the absence of catalysts and additives in

a scalable and practical manner in common grade solvents and without deoxygenation of the reaction mixtures (Figure 1).
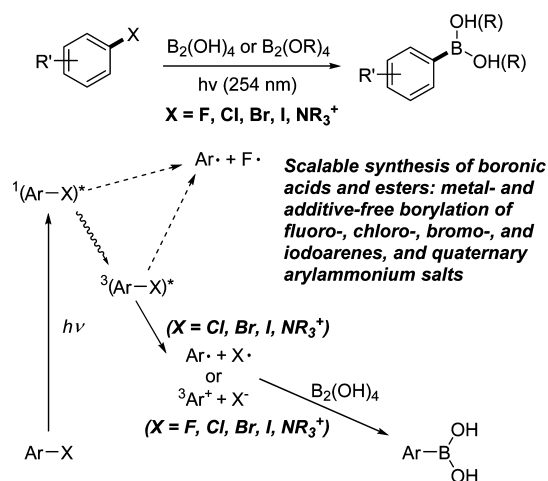


**Figure 1.** Photoinduced borylation.

Initial experiments showed that a reaction of bromobenzene with tetrahydroxydiboron in methanol under ultraviolet irradiation ($\lambda$ = 254 nm) produced phenylboronic acid (**1**) in 92% yield after 3 h at 15 °C. The optimal temperature was 10−20 °C, with increased amounts of benzene observed at higher temperatures. The reaction did not proceed in the dark (see Table S1) and showed a good quantum yield ($\Phi$ = 0.34).

The preparative scope of the reaction was explored with a series of substituted bromoarenes. A diverse set of functional groups is well tolerated, including amide (**2**, 71%), phenol (**3**, 73%), arylacetate ester (**4**, 85%), thioether (**5**, 79% and **6**, 69%), and other functionalities (**7−25**). Both electron-releasing and electron-withdrawing substituents can be very well accommodated. Nitrogen-, oxygen-, and sulfur-containing heteroarylboronic acids were also prepared in high yields, as shown for products **7−11**. The boronic acids can be directly converted into the corresponding organotrifluoroborates as a part of the isolation procedure. For example, the borylation reaction of 3-bromoquinoline was followed by treatment of the reaction mixture with potassium difluoride[25] to give the corresponding trifluoroborate **11** in 81% yield.

Iodoarenes and chloroarenes were also successfully converted to boronic acids. The reactions with iodoarenes were very fast
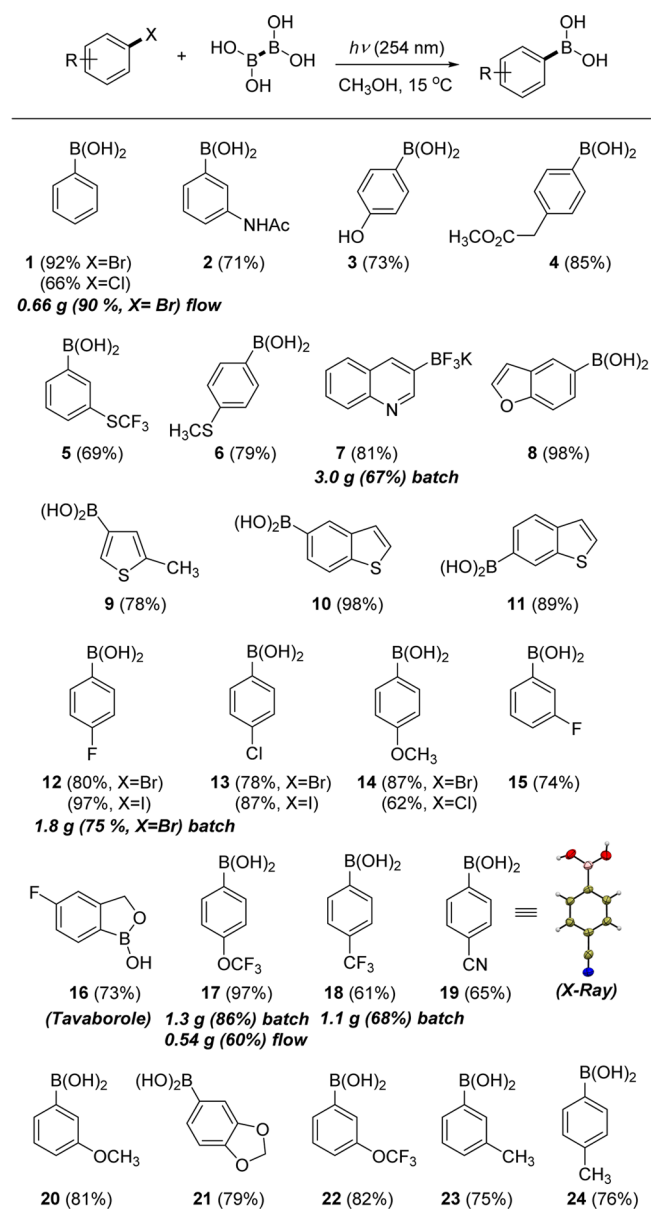
and produced the boronic acids (**12** and **13**) in high yields within 1 h. Chloroarenes reacted slower than bromoarenes (66% of **1** and 62% of **14** after 24 h). These observations are in accord with the increase in the bond dissociation energies (BDE) of the $C_6H_5-X$ bonds (C–I 272, C–Br 336, C–Cl 400 kJ·mol$^{-1}$).[26] The differential reactivity of C–X bonds can be used for the chemoselective and high-yielding synthesis of haloarylboronic acids, as shown for **12**, **13**, **15**, and **16**.

Boronic acids find increasing use in medicine,[7] as exemplified by the fungal leucyl-tRNA synthetase inhibitor tavaborole (**16**, Table 1) that has recently been approved for treatment of onychomycosis.[27] Using the photoinduced borylation, **16** was prepared from the corresponding bromoarene in 73% yield after a simple workup. Tavaborole was previously prepared using air- and moisture-sensitive reagents (NaH, *n*-BuLi, and B(O*i*Pr)$_3$).[28] The successful synthesis of **16** also indicates that an ortho-substituent is well-tolerated during the borylation event. Furthermore, good quantum efficiency of the borylation reaction enabled practical gram-scale syntheses of several representative boronic acids (**12**, **17**, **18** on 1.1–1.8 g scales) and trifluoroborate **7** (3 g) using simple quartz test tubes and low-intensity UV sources without deoxygenation of the reaction solutions.

Fluorobenzene proved resistant to the borylation in line with the high BDE of the $C_6H_5-F$ bond (526 kJ·mol$^{-1}$)[26] that exceeds the energy of absorbed light (469 kJ·mol$^{-1}$). Remarkably, 4-fluoroaniline readily produced (4-aminophenyl)boronic acid that was isolated as trifluoroborate **25** in 53% yield, indicating that certain Ar–F bonds can be harnessed for the synthesis of boronic acids without the use of transition metals.[29] Similarly, 4-fluorophenol reacted smoothly to give boronic acid **3** in 69% yield (Table 2). Other fluoroarenes bearing electron-releasing substituents are also competent substrates (**26**–**30**). The procedure is particularly suitable for borylation of unprotected fluoroanilines and fluorophenols that have so far eluded C–F borylation. The reactivity observed for 4-fluoroanline and other similar fluoroarenes in the photoinduced borylation reaction is consistent with the formation of the triplet aryl cation via the heterolysis of the C–F bond. This process is favored for the electron-rich haloarenes and, unlike Ar–F homolysis, is greatly facilitated in polar protic solvents, as previously described by Albini, Fagnoni, and Protti.[30] Indeed, the yield of the reaction of 4-fluorophenol with B$_2$pin$_2$ was solvent dependent. No reaction was observed in hexane after 2 h, and only 5% of the borylation product was formed in acetonitrile, while 20% of the borylation product was produced in methanol. This observation is in line with the experimental and computational data reported for the photoinduced heterolysis of 4-fluorophenol.[30] Although B$_2$(OR)$_4$ generally behave as electrophiles, complexation with Lewis bases (e.g., fluoride, alkoxides, N-heterocyclic carbenes, 4-methylpyridine, and phosphines)[31] produces nucleophilic sp$^2$–sp$^3$ Lewis base–diboron adducts that react with organic electrophiles in the absence of transition-metal catalysts.[32] It is possible that the photoheterolytically produced fluoride ion forms a transient nucleophilic sp$^2$–sp$^3$ B$_2$(OR)$_4$F$^-$ complex that then reacts with the triplet cation.[33] Interestingly, B$_2$pin$_2$F$^-$ adduct was proposed as an intermediate in the borylation of arenediazonium salts,[13c] and [NMe$_4$][B$_2$pin$_2$F] was subsequently shown to effect the diazonium borylation.[31d] The photoinduced borylation of fluoroarenes is the first example of metal-free and direct conversion of fluoroarenes to arylboronic acids.

Encouraged by the outcome of the experiments with haloarenes, we turned our attention to the borylation of other
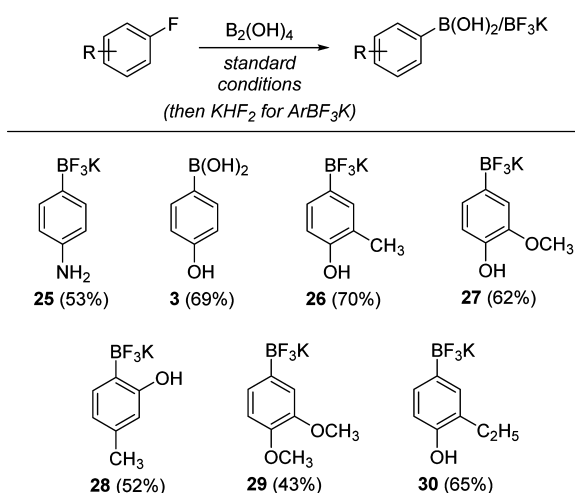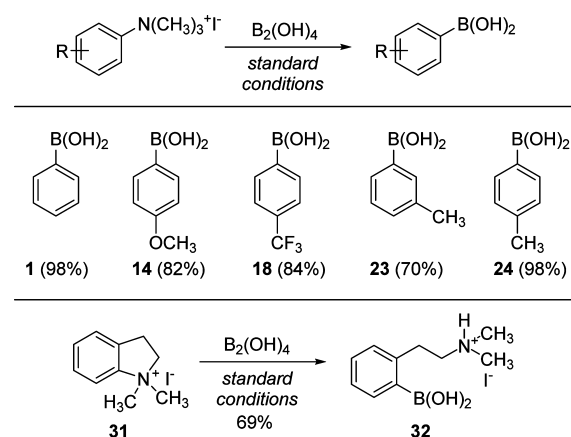
**Table 1. Scope of the Photoinduced Reaction of Haloarenes with Tetrahydroxydiboron**[a]



[a] Bromoarenes were used unless specified otherwise. Reaction conditions for small-scale experiments: haloarene (0.6–1 mmol), tetrahydroxydiboron (1–1.6 mmol), CH$_3$OH (5–6 mL), 15 °C, 3–24 h, UV lamp (254 nm); then treatment with KHF$_2$ for ArBF$_3$K. Preliminary experiments also show that the reaction can be translated to a continuous flow process (**1**, 90% and **17**, 60%). Reaction mixtures typically remained homogeneous. Monitoring of the borylation reactions by $^{11}$B NMR indicated formation of trimethyl borate that may arise from solvolysis of B–X bond-containing inorganic byproducts of the reaction.

carbon–heteroatom bonds. In particular, we focused on the Ar–N borylation, since few methods are known for this transformation.[13,34] Interestingly, aryltrimethylammonium iodides reacted rapidly and produced the corresponding boronic acids **1**, **14**, **18**, **23**, and **24** in 70–98% yields. In addition, ring scission of the cyclic salt **31** afforded boronic acid **32** in 69% yield (Table 3).
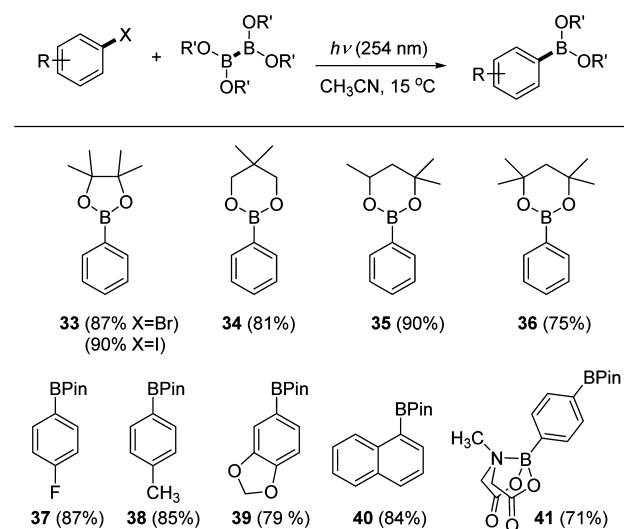
We next evaluated several diboron esters as counterparts in the reaction with haloarenes (Table 4). The borylation reactions with diboron esters derived from pinacol, neopentyl glycol, 1,1,3-

**Table 2. Borylation of Fluoroarenes**[a]



[a]Reaction conditions: see Table 1 footnote.

**Table 3. Borylation of Quaternary Arylammonium Salts**[a]



[a]Reaction conditions: see Table 1 footnote.

trimethylethylene glycol, and 1,1,4,4,-tetramethylethylene glycol delivered the corresponding phenylboronic esters **33−36** in high yields using acetonitrile as a solvent. The reaction scope was further tested with several bromoarenes with varied substitution patterns. In all cases the corresponding borolanes **37−40** were produced in excellent yields without any noticeable photo-transposition.[35] Interestingly, the MIDA boronate ester **41** was also prepared, indicating that bifunctional borylated arenes can be efficiently accessed using this method.

Although further work is necessary to clarify the mechanism, it is possible that homolytic substitution[36] in the diboron reagents and sp[2]–sp[3] Lewis base−diboron adducts by a photogenerated aryl radical and aryl triplet cation can be responsible for the observed reactivity.[33]

In summary, this paper describes a simple, scalable, metal- and additive-free method of photoinduced borylation of haloarenes and quaternary arylammonium salts. The borylation produces aromatic boronic acids and esters in good to excellent yields under mild conditions and with formation of innocuous, easy-to-remove byproducts. The reaction is distinguished by a broad scope that includes electron-rich fluoroarenes.

**Table 4. Photoinduced Reaction of Haloarenes with Diboronic Esters**[a]



[a]Bromoarenes were used unless specified otherwise. Reaction conditions: haloarene (0.5−1 mmol), diboron ester (1−2 mmol), CH$_3$CN (6 mL), 15 °C, 4−14 h, UV lamp (254 nm). Bpin = 4,4,5,5-tetramethyl-1,3,2-dioxaborolane.

## ■ ASSOCIATED CONTENT

**Ⓢ Supporting Information**

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/jacs.6b01376.

Experimental details and data (PDF)
(CIF)

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**Notes**

The authors declare no competing financial interest.

## ■ REFERENCES

(1) (a) Suzuki, A.; Brown, H. C. *Organic Syntheses Via Boranes*; Aldrich Chemical Company: Milwakee, 2003; Vol 3. (b) *Boronic Acids*, 2nd ed.; Hall, D. G., Ed.; Wiley-VCH: Weinheim, 2011. (c) Gutekunst, W. R.; Baran, P. S. *Chem. Soc. Rev.* **2011**, *40*, 1976.

(2) (a) Corey, E. J. *Angew. Chem., Int. Ed.* **2002**, *41*, 1650. (b) Dimitrijević, E.; Taylor, M. S. *ACS Catal.* **2013**, *3*, 945. (c) Ishihara, K. *Top. Organomet. Chem.* **2015**, *49*, 243. (d) Taylor, M. S. *Acc. Chem. Res.* **2015**, *48*, 295.

(3) (a) Fujita, N.; Shinkai, S.; James, T. D. *Chem. - Asian J.* **2008**, *3*, 1076. (b) Mastalerz, M. *Angew. Chem., Int. Ed.* **2010**, *49*, 5042.

(4) (a) James, T. D.; Shinkai, S. *Top. Curr. Chem.* **2002**, *218*, 159. (b) Jelinek, R.; Kolusheva, S. *Chem. Rev.* **2004**, *104*, 5987. (c) Pal, A.; Berube, M.; Hall, D. G. *Angew. Chem., Int. Ed.* **2010**, *49*, 1492. (d) Hansen, J. S.; Christensen, J. B.; Petersen, J. F.; Hoeg-Jensen, T.; Norrild, J. C. *Sens. Actuators, B* **2012**, *161*, 45.

(5) (a) Wade, C. R.; Broomsgrove, A. E. J.; Aldridge, S.; Gabbaï, F. P. *Chem. Rev.* **2010**, *110*, 3958. (b) Wu, X.; Li, Z.; Chen, X.-X.; Fossey, J. S.;

James, T. D.; Jiang, Y. B. *Chem. Soc. Rev.* **2013**, *42*, 8032. (c) Guan, Y.; Zhang, Y. *Chem. Soc. Rev.* **2013**, *42*, 8106. (d) You, L.; Zha, D.; Anslyn, E. V. *Chem. Rev.* **2015**, *115*, 7840. (e) Wu, J.; Kwon, B.; Liu, W.; Anslyn, E. V.; Wang, P.; Kim, J. S. *Chem. Rev.* **2015**, *115*, 7893.

(6) (a) Lorbach, A.; Huebner, A.; Wagner, M. *Dalton Trans.* **2012**, *41*, 6048. (b) Liu, J.; Lavigne, J. J. In *Boronic Acids*, 2nd ed.; Hall, D. G., Ed.; Wiley-VCH: Weinheim, 2011. (c) Jäkle, F. *Top. Organomet. Chem.* **2015**, *49*, 297.

(7) (a) Trippier, P. C.; McGuigan, C. *MedChemComm* **2010**, *1*, 183. (b) Yang, W.; Gao, W.; Wang, B. Biological and Medicinal Applications of Boronic Acids. In *Boronic Acids*; Hall, D. G., Ed.; Wiley-VCH: Weinheim, 2011. (c) Ban, H. S.; Nakamura, H. *Chem. Rec.* **2015**, *15*, 616.

(8) Khotinsky, E.; Melamed, M. *Ber. Dtsch. Chem. Ges.* **1909**, *42*, 3090.

(9) Letsinger, R. L.; Skoog, I. H. *J. Org. Chem.* **1953**, *18*, 895.

(10) (a) Ishiyama, T.; Murata, M.; Miyaura, N. *J. Org. Chem.* **1995**, *60*, 7508. (b) Murata, M.; Watanabe, S.; Masuda, Y. *J. Org. Chem.* **1997**, *62*, 6458. (c) Ishiyama, T.; Miyaura, N. *J. Organomet. Chem.* **2000**, *611*, 392. (d) Ishiyama, T.; Miyaura, N. In *Boronic Acids*, 2nd ed.; Hall, D. G., Ed.; Wiley-VCH: Weinheim, 2011. (e) Chow, W. K.; Yuen, O. Y.; Choy, P. Y.; So, C. M.; Lau, C. P.; Wong, W. T.; Kwong, F. Y. *RSC Adv.* **2013**, *3*, 12518.

(11) (a) Cho, J.-Y.; Tse, M. K.; Holmes, D.; Maleczka, R. E.; Smith, M. R. *Science* **2002**, *295*, 305. (b) Mkhalid, I. A. I.; Barnard, J. H.; Marder, T. B.; Murphy, J. M.; Hartwig, J. F. *Chem. Rev.* **2010**, *110*, 890. (c) Hartwig, J. F. *Acc. Chem. Res.* **2012**, *45*, 864. (d) Stahl, T.; Muether, K.; Ohki, Y.; Tatsumi, K.; Oestreich, M. *J. Am. Chem. Soc.* **2013**, *135*, 10978.

(12) (a) Yamamoto, E.; Izumi, K.; Horita, Y.; Ito, H. *J. Am. Chem. Soc.* **2012**, *134*, 19997. (b) Nagashima, Y.; Takita, R.; Yoshida, K.; Hirano, K.; Uchiyama, M. *J. Am. Chem. Soc.* **2013**, *135*, 18730. (c) Zhang, J.; Wu, H.-H.; Zhang, J. *Eur. J. Org. Chem.* **2013**, *2013*, 6263. (d) Yamamoto, E.; Izumi, K.; Horita, Y.; Ukigai, S.; Ito, H. *Top. Catal.* **2014**, *57*, 940.

(13) (a) Mo, F.; Jiang, Y.; Qiu, D.; Zhang, Y.; Wang, J. *Angew. Chem., Int. Ed.* **2010**, *49*, 1846. (b) Yu, J.; Zhang, L.; Yan, G. *Adv. Synth. Catal.* **2012**, *354*, 2625. (c) Zhu, C.; Yamane, M. *Org. Lett.* **2012**, *14*, 4560. (d) Qiu, D.; Jin, L.; Zheng, Z.; Meng, H.; Mo, F.; Wang, X.; Zhang, Y.; Wang, J. *J. Org. Chem.* **2013**, *78*, 1923.

(14) (a) De Vries, T. S.; Prokofjevs, A.; Vedejs, E. *Chem. Rev.* **2012**, *112*, 4246. (b) Ingleson, M. J. *Synlett* **2012**, *23*, 1411. (c) Ingleson, M. J. *Top. Organomet. Chem.* **2015**, *49*, 39. (d) Warner, A. J.; Lawson, J. R.; Fasano, V.; Ingleson, M. J. *Angew. Chem., Int. Ed.* **2015**, *54*, 11245.

(15) (a) Schutt, L.; Bunce, N. G. In *CRC Handbook of Organic Photochemistry and Photobiology*, 2nd ed.; Horspool, W. M., Lenci, F., Eds.; CRC Press: Boca Raton, 2004. (b)　*Handbook of Synthetic Photochemistry*; Albini, A., Fagnoni, M., Eds.; Wiley-VCH: Weinheim, 2010. (c) Albini, A.; Fagnoni, M. *Photochemically-Generated Intermediates in Synthesis*; John Wiley & Sons, Inc.: Hoboken, 2013.

(16) (a) Pape, M. *Pure Appl. Chem.* **1975**, *41*, 535. (b) Weissermal, K.; Arpe, H.-J. *Industrial Organic Chemistry*, 3th ed.; VCH: Weinheim, 1997; p 254.

(17) Ravelli, D.; Protti, S.; Neri, P.; Fagnoni, M.; Albini, A. *Green Chem.* **2011**, *13*, 1876.

(18) (a) Zhu, G.-D.; Okamura, W. H. *Chem. Rev.* **1995**, *95*, 1877. (b) Labler, L. Vitamins 3. Vitamin D. *Ullmann's Encyclopedia of Industrial Chemistry*, 7th ed; Wiley-VCH: Weinheim, 2011.

(19) For recent examples, see: (a) Yoshimura, A.; Takamachi, Y.; Han, L.-B.; Ogawa, A. *Chem. - Eur. J.* **2015**, *21*, 13930. (b) Brimioulle, R.; Bauer, A.; Bach, T. *J. Am. Chem. Soc.* **2015**, *137*, 5170. (c) Mukhina, O. A.; Kutateladze, A. G. *J. Am. Chem. Soc.* **2016**, *138*, 2110.

(20) (a) Bunnett, J. F. *Acc. Chem. Res.* **1978**, *11*, 413. (b) Karapire, C.; Siddik, I. In *CRC Handbook of Organic Photochemistry and Photobiology*, 2nd ed.; Horspool, W. M., Lenci, F., Eds.; CRC Press: Boca Raton, 2004. (c) Uyeda, C.; Tan, Y. C.; Fu, G. C.; Peters, J. C. *J. Am. Chem. Soc.* **2013**, *135*, 9548. (d) Tan, Y. C.; Munoz-Molina, J. M.; Fu, G. C.; Peters, J. C. *Chem. Sci.* **2014**, *5*, 2831. (e) Li, L.; Liu, W.; Zeng, H.; Mu, X.; Cosa, G.; Mi, Z.; Li, C.-J. *J. Am. Chem. Soc.* **2015**, *137*, 8328.

(21) (a) Dichiarante, V.; Fagnoni, M.; Albini, A. *Angew. Chem., Int. Ed.* **2007**, *46*, 6495. (b) Buden, M. E.; Guastavino, J. F.; Rossi, R. A. *Org. Lett.* **2013**, *15*, 1174. (c) Ruch, J.; Aubin, A.; Erbland, G.; Fortunato, A.; Goddard, J.-P. *Chem. Commun.* **2016**, *52*, 2326.

(22) (a) Mella, M.; Coppo, P.; Guizzardi, B.; Fagnoni, M.; Freccero, M.; Albini, A. *J. Org. Chem.* **2001**, *66*, 6344. (b) Guizzardi, B.; Mella, M.; Fagnoni, M.; Albini, A. *Chem. - Eur. J.* **2003**, *9*, 1549. (c) Zheng, X. L.; Yang, L.; Du, W. Y.; Ding, A. S.; Guo, H. *Chem. - Asian J.* **2014**, *9*, 439.

(23) (a) Grimshaw, J.; de Silva, A. P. *Chem. Soc. Rev.* **1981**, *10*, 181. (b) Park, Y. T.; Song, N. W.; Hwang, C. G.; Kim, K. W.; Kim, D. *J. Am. Chem. Soc.* **1997**, *119*, 10677. (c) Lu, S. C.; Zhang, X. X.; Shi, Z. J.; Ren, Y. W.; Li, B.; Zhang, W. *Adv. Synth. Catal.* **2009**, *351*, 2839.

(24) For Pd- and Ni-catalyzed borylation with tetrahydroxydiboron, see: (a) Molander, G. A.; Trice, S. L. J.; Dreher, S. D. *J. Am. Chem. Soc.* **2010**, *132*, 17701. (b) Molander, G. A.; Trice, S. L. J.; Kennedy, S. M.; Dreher, S. D.; Tudge, M. T. *J. Am. Chem. Soc.* **2012**, *134*, 11667. (c) Molander, G. A.; Trice, S. L. J.; Kennedy, S. M. *J. Org. Chem.* **2012**, *77*, 8678. (d) Molander, G. A.; Trice, S. L.; Kennedy, S. M. *Org. Lett.* **2012**, *14*, 4814. (e) Molander, G. A.; Cavalcanti, L. N.; Garcia-Garcia, C. *J. Org. Chem.* **2013**, *78*, 6427.

(25) (a) Vedejs, E.; Chapman, R. W.; Fields, S. C.; Lin, S.; Schrimpf, M. R. *J. Org. Chem.* **1995**, *60*, 3020. (b) Molander, G. A.; Ellis, N. *Acc. Chem. Res.* **2007**, *40*, 275. (c) Darses, S.; Genet, J.-P. *Chem. Rev.* **2008**, *108*, 288. (d) Molander, G. A.; Jean-Gérard, L. In *Boronic Acids*, 2nd ed.; Hall, D. G., Ed.; Wiley-VCH: Weinheim, 2011.

(26) Luo, Y.-R. *Comprehensive Handbook of Chemical Bond Energies*; CRC Press: Boca Raton, 2007.

(27) (a) Baker, S. J.; Zhang, Y.-K.; Akama, T.; Lau, A.; Zhou, H.; Hernandez, V.; Mao, W.; Alley, M. R. K.; Sanders, V.; Plattner, J. J. *J. Med. Chem.* **2006**, *49*, 4447. (b) Rock, F. L.; Mao, W.; Yaremchuk, A.; Tukalo, M.; Crépin, T.; Zhou, H.; Zhang, Y.-K.; Hernandez, V.; Akama, T.; Baker, S. J.; Plattner, J. J.; Shapiro, L.; Martinis, S. A.; Benkovic, S. J.; Cusack, S.; Alley, M. R. K. *Science* **2007**, *316*, 1759.

(28) Gunasekera, D. S.; Gerold, D. J.; Aalderks, N. S.; Chandra, J. S.; Maanu, C. A.; Kiprof, P.; Zhdankin, V. V.; Reddy, M. V. R. *Tetrahedron* **2007**, *63*, 9401.

(29) For Ni-catalyzed borylation of fluoroarenes, see: (a) Liu, X.-W.; Echavarren, J.; Zarate, C.; Martin, R. *J. Am. Chem. Soc.* **2015**, *137*, 12470. (b) Niwa, T.; Ochiai, H.; Watanabe, Y.; Hosoya, T. *J. Am. Chem. Soc.* **2015**, *137*, 14313.

(30) (a) Freccero, M.; Fagnoni, M.; Albini, A. *J. Am. Chem. Soc.* **2003**, *125*, 13182. (b) Fagnoni, M.; Albini, A. *Acc. Chem. Res.* **2005**, *38*, 713. (c) Dichiarante, V.; Fagnoni, M. *Synlett* **2008**, *2008*, 787. (d) Raviola, C.; Ravelli, D.; Protti, S.; Albini, A.; Fagnoni, M. *Synlett* **2015**, *26*, 471.

(31) (a) Nguyen, P.; Dai, C.; Taylor, N. J.; Power, W. P.; Marder, T. B.; Pickett, N. L.; Norman, N. C. *Inorg. Chem.* **1995**, *34*, 4290. (b) Clegg, W.; Dai, C.; Lawlor, F. J.; Marder, T. B.; Nguyen, P.; Norman, N. C.; Pickett, N. L.; Power, W. P.; Scott, A. J. *J. Chem. Soc., Dalton Trans.* **1997**, 839. (c) Kleeberg, C.; Crawford, A. G.; Batsanov, A. S.; Hodgkinson, P.; Apperley, D. C.; Cheung, M. S.; Lin, Z.; Marder, T. B. *J. Org. Chem.* **2012**, *77*, 785. (d) Pietsch, S.; Neeve, E. C.; Apperley, D. C.; Bertermann, R.; Mo, F.; Qiu, D.; Cheung, M. S.; Dang, L.; Wang, J.; Radius, U.; Lin, Z.; Kleeberg, C.; Marder, T. B. *Chem. - Eur. J.* **2015**, *21*, 7082.

(32) (a) Lee, K.-s.; Zhugralin, A. R.; Hoveyda, A. H. *J. Am. Chem. Soc.* **2009**, *131*, 7253. (b) Bonet, A.; Gulyas, H.; Fernandez, E. *Angew. Chem., Int. Ed.* **2010**, *49*, 5130. (c) Bonet, A.; Pubill-Ulldemolins, C.; Bo, C.; Gulyas, H.; Fernandez, E. *Angew. Chem., Int. Ed.* **2011**, *50*, 7158. (d) Wu, H.; Radomkit, S.; O'Brien, J. M.; Hoveyda, A. H. *J. Am. Chem. Soc.* **2012**, *134*, 8277. (e) Bonet, A.; Sole, C.; Gulyas, H.; Fernandez, E. *Org. Biomol. Chem.* **2012**, *10*, 6621.

(33) See Scheme S1 and further discussion in the SI.

(34) (a) Tobisu, M.; Nakamura, K.; Chatani, N. *J. Am. Chem. Soc.* **2014**, *136*, 5587. (b) Hu, J.; Sun, H.; Cai, W.; Pu, X.; Zhang, Y.; Shi, Z. *J. Org. Chem.* **2016**, *81*, 14.

(35) Cameron, K. S.; Pincock, A. L.; Pincock, J. A.; Thompson, A. *J. Org. Chem.* **2004**, *69*, 4954.

(36) (a) Davies, A. G.; Roberts, B. P.; Scaiano, J. C. *J. Chem. Soc. B* **1971**, 2171. (b) Nozaki, K.; Oshima, K.; Utimoto, K. *Bull. Chem. Soc. Jpn.* **1991**, *64*, 403. (c) Brown, H. C.; Midland, M. M. *Angew. Chem., Int. Ed. Engl.* **1972**, *11*, 692. (d) Ollivier, C.; Renaud, P. *Chem. Rev.* **2001**, *101*, 3415.