

Electrochemical Radical Borylation of Aryl Iodides[†]

Junting Hong,^{‡,a} Qianyi Liu,^{‡,a} Feng Li,^b Guangcan Bai,^b Guoquan Liu,^b Man Li,^a Onkar S. Nayal,^a Xuefeng Fu,^c and Fanyang Mo*^{,a,d}

^a Department of Energy and Resources Engineering, College of Engineering, Peking University, Beijing 100871, China

^b State Key Laboratory of Natural and Biomimetic Drugs, School of Pharmaceutical Sciences, Peking University, Beijing 100871, China

^c Department of Biomedical Engineering, College of Engineering, Peking University, Beijing 100871, China

^d Jiangsu Donghai Silicon Industry S&T Innovation Center, Jiangsu Weiming Environmental Protection S&T Co., Ltd., No. 38, Guangming Rd, Donghai County, Jiangsu 222300, China

Cite this paper: Chin. J. Chem. 2019, 37, 347-351. DOI: 10.1002/cjoc.201900001

Summary of main observation and conclusion Herein, we report the first electrochemical strategy for the borylation of aryl iodides *via* a radical pathway using current as a driving force. A mild reaction condition allows an assorted range of readily available aryl iodides to be proficiently converted into synthetically valuable arylboronic esters under transition metal catalyst-free conditions. Moreover, this method also shows good functional group tolerance. Initial control mechanistic experiments reveal the formation of aryl radical as a key intermediate and the current plays an important role in the generation of radical intermediate.

Background and Originality Content

Arylboronic acids and their derivatives possess widespread applications in organic synthesis.^[1] Consequently, the methods of their preparation have been intensively developed in the past decades. Conventional approaches to the synthesis of arylboronic acids or esters from aryl halides require either prior preparation of highly reactive organometallic reagents,^[2] or the procedures^[3] required transition-metal such as Pd,^[4] Ni,^[5] Cu,^[6] Zn^[7] and Fe^[8] as a catalyst. These methods are widely used in laboratories and pharmaceutical companies. However, the limited functional group compatibility and the use of expensive metals and/or ligands or strong bases are the obvious drawbacks in these methods. Nevertheless, there is a strong need to the development of efficient, mild, and transition-metal-free synthetic approach for the borylation of aryl halides.

In this context, organic electrochemistry offers a green and sustainable alternative tool to conventional chemical approaches for organic transformations.^[9] Various versatile reactive intermediate (*e.g.*, radical cation, radical anion, and radical) can be efficiently generated by anodic oxidation, cathodic reduction, as well as paired electrolysis. Our laboratory has been engaged in the development of organic electrochemistry to overcome unmet synthetic challenges.^[10] With this background, we thought to synthesize aryl boronates from aryl halides through electrochemical transformation (Scheme 1c).

In the context of electro-reduction of aryl halides, it's well known that aryl halide easily transforms to aryl radical *via* a reversible, dissociative electron transfer (DET) process. Ensuing, this radical is widely used in various organic transformations (Scheme 1a).^[11] Except this strategy, transition-metal-free borylation approaches are also well known for the synthesis of a diverse range of organoboron compounds *via* radical pathway.^[12] Since the pioneering work of Wang group in 2010,^[13] numerous transition-metal-free aromatic borylation protocols have been developed using anilines,^[14] aryl (pseudo)halides,^[15] and aryl carboxylates^[16]

Scheme 1 Electrochemical borylation of aryl halides

(a) Well-known electroreduction of aryl halide process

$$ar - x + e \xrightarrow{cathode} [Ar - x]^{-} \longrightarrow Ar^{-} + x$$

(b) Well-established borylation via radical mechanism

(c) Electrochemical radical borylation of aryl iodides (this work)

Sustainable process (no sacrificing anode, no electrolyte)

Soft conditions (not sensitive to air or moisture)
 Simple operation (undivided cell)

as the coupling substrates (Scheme 1b). Inspired from these strategies, we thought to develop an electro chemical radical borylation of aryl halides *via* cathodic reduction under transition-metal-free condition (Scheme 1c).

Herein, we present mild radical borylation of aryl halides with commercially available bis(pinacolato)diboron (B₂pin₂), as the boron source. After the comparison of the present study with the known borylation methods, we found that the electrochemical radical borylation reaction has many advantages over the known protocols. Primarily, the overall process is sustainable, in which electron serves as the reductant with solvents being oxidized at the anode, therefore, no sacrificing anode is needed. Furthermore, this reaction can be performed under air atmosphere. Moreover, this electrochemical radical borylation of aryl iodides approach got remarkable increase in reaction rate over the reported work on borylation of aryl iodides by Zhang's group under the similar reaction conditions.^[15e]

*E-mail: fmo@pku.edu.cn

For submission: https://mc.manuscriptcentral.com/cjoc For articles: https://onlinelibrary.wiley.com/journal/16147065

[†] These authors contributed equally to this work.

⁺ Dedicated to the Special Issue of "Organic Electrochemistry".

Results and Discussion

In this investigation, we chose phenyl iodide 1a as a model substrate and pinacol diboron ($B_2 \text{pin}_2)\ \textbf{2}$ as a borylating agent (Table 1). Interestingly, 54% yield of 3a was obtained using platinum meshes as the electrodes with 13 mA constant current in the presence of cesium carbonate (entry 1). Notably, either increasing or decreasing the current resulted in lower yields (entries 2 and 3). After that, other bases such as CsF, CsOAc, t-BuOK and MeONa were also investigated under similar reaction conditions. However, all these bases were less effective (entries 4–5 and 7–8). To our delight, the significant change was observed in the yield of the desired product after the elevation of reaction temperature in 2 h (entry 6). Moreover, other solvents, such as EtOH, THF and MeCN were also tested to optimize the best reaction solvent. Regrettably, no better yield of 3a was obtained (entries 9-11). In the cases of THF and MeCN solvents, the reaction media became less conductive (30 V, 1-3 mA). Therefore, electrolyte Bu₄NClO₄ was added in the reaction media to succeed the reaction (entries 10-11). After the screening of additional reaction time, it is revealed that 3 h is the optimum time for the completion of the reaction (entry 12). Moreover, drastically changes were observed in the yield of the desired product after increasing the amount of B₂pin₂ from 3.0 and 4.0 equiv. (entry 1 and entries 12-13). Finally, in the absence of current, deleterious impact was observed in the yield of 3a (entry 14), which indicates clearly the significant role of current in the generation of aryl radical. Moreover, the "on and off" experiment also indicated the requirement of continuous current (entry 15).

With the optimal reaction conditions in hand, we explored the substrate scope of aryl iodide (Table 2). Notably, a wide range of aryl iodide derivatives bearing both electron-withdrawing and electron-donating groups could be borylated in moderate to good yields. Aryl iodides with an electron-donating group furnished the corresponding borylation product in good yields (**3a**—**3e**). A ste-

rically hindered aryl iodide such as **2e** and **2f** engaged smoothly in the reaction and afforded a moderate yield of the respective product. In addition, aryl iodides with an electron-withdrawing group, such as an amide and an ester, produced borylation products in moderate yields (3g-3j). Notably, for substrate 1j', the ester group was converted to phenolic hydroxyl and furnished product 3j in 60% yield.

To study the mechanism, we designed a series of electron paramagnetic resonance (EPR) experiments. In this context, dimethylpyridine *N*-oxide (DMPO) was introduced as a spin trapping agent to convert the short-living active radical into EPR detectable nitroxide radicals.^[17] The EPR spectra were simulated using the least-squares fitting method with EasySpin's function *garlic* (for details, see Supporting Information). The parameters, isotropic *g* values and hyperfine constants *A* were carefully compared with literature data and used as the unique fingerprint of the trapped radicals.

Interestingly, when the current is passed through in a reaction medium for 5 min at room temperature, the strong EPR signal appears (Figure 1a). Besides, in the absence of current, the intensity of EPR signal is decreased under similar conditions. This EPR signal is generally assigned to be DMPO-Ph, which is already known in various reported literatures.^[18] However, on the basis of previous reports, we found that the signals of some other species such as DMPO·CH₃,^[18b,19] DMPO·CH₂OH,^[19,20] appear very close or are similar to the EPR signal of DMPO·Ph. To verify an electrochemically generating radical species by the reduction of halides on cathode process, we carried out the reaction with $n-C_4F_9I$ in the presence of 45 mA current. As expected, a very special "quasi-quartet" signal of DMPO $C_4 F_9^{[19]}$ appears within 30 min shown in Figure 1b due to the inductive effect caused by the adjacent fluorine substituents. On the basis of results of control experiments presented in Supporting Information, the mentioned literatures and the cyclic voltammetry studies (vide infra), we

		1;	a (0.5 mmol)	2	Base (2.0 equiv) Solvent (5 mL) <i>T</i> , time undivided cell	Ja Ja		
Entry	Base	1a/2/ Base	Current/mA	<i>T/</i> °C	Time/h	Solvent	Conv. of 1a ^b /%	Yield ^b /%
1	Cs_2CO_3	1:3:2	10	50	1	MeOH	69	44
2	Cs_2CO_3	1:3:2	13	50	1	MeOH	61	54
3	Cs_2CO_3	1:3:2	20	50	1	MeOH	79	52
4	CsF	1:3:2	13	50	1	MeOH	71	33
5	CsOAc	1:3:2	13	50	1	MeOH	58	16
6	Cs_2CO_3	1:3:2	13	65	2	MeOH	100	64
7	^t BuOK	1:3:2	13	65	2	MeOH	51	40
8	MeONa	1:3:2	13	65	2	MeOH	59	44
9	Cs_2CO_3	1:3:2	13	78	2	EtOH	85	30
10	Cs_2CO_3	1:3:2	13	65	2	THF	40	34
11	Cs_2CO_3	1:3:2	13	65	2	MeCN ^c	64	11
12	Cs ₂ CO ₃	1:4:2	13	65	3	MeOH	98	76
13	Cs_2CO_3	1:3.5:2	13	65	3	MeOH	97	67
14	Cs_2CO_3	1:4:2	0	65	3	MeOH	19	14
15 ^d	Cs_2CO_3	1:4:2	0—13	65	3	MeOH	52	33

 Table 1
 Reaction optimization^a

Pt(+)/Pt(-), cc

^{*a*} Reaction conditions: Platinum mesh electrodes (1 cm × 1 cm), **1a** (0.5 mmol), **2**, base (2.0 equiv.), solvent (5 mL), heating, undivided cell, sealed tube. cc, constant current. ^{*b*} Determined by GC-FID with *n*-decane as an internal standard. ^{*c*} Bu₄NClO₄ as the electrolyte was added. ^{*d*} "On and off" control experiment. During a total time of 3 h, the current continued for 3 min and then interrupted for 27 min, cycled for 6 times.



^{*a*} Reaction conditions: **1** (0.5 mmol), **2** (2.0 mmol, 4.0 equiv.), Cs_2CO_3 (1.0 mmol, 2.0 equiv.), MeOH (5 mL), platinum mesh electrodes (1 cm × 1 cm), constant current 13 mA, 65 °C, 3 h, undivided cell, sealed tube. ^{*b*} Using reticulated vitreous carbon (RVC) electrodes. ^{*c*} From **1j**'.



Figure 1 EPR experiments. Reaction conditions: iodides (0.3 mmol), B_2Pin_2 (1.2 mmol, 4.0 equiv.), Cs_2CO_3 (0.6 mmol, 2.0 equiv.), DMPO (0.3 mmol, 30 µL), MeOH (3 mL), platinum mesh electrodes (1 cm × 1 cm), stirred at room temperature with given current and time.

Chin. J. Chem.

concluded that the strong EPR signal appears due to the formation of DMPO·Ph species in Figure 1a. Thus, these results indicate the generation of aryl radicals and current enhance the rate of aryl radical formation.

To further clarify the reduction process of iodides, we designed cyclic voltammetry (CV) measurements. Initially, when we mixed phenyl iodide **1a** with LiClO₄ solution, a single reduction peak appeared, which is shown in Figure 2a. Noteworthy, after the addition of B_2pin_2 and base Cs_2CO_3 in the model reaction, the single reduction peak appeared with a sharp band. While this peak disappeared completely in the absence of phenyl iodide **1a** as shown in Figure 2b. Thus, these results indicate the single electron reduction process of aryl iodides on the cathode. In addition, we conducted differential pulsed voltammetry (DPV) experiments to further confirm the single electron reduction of aryl iodide shown in Supporting Information.





Figure 2 Cyclic voltammetry (CV) experiments. Reaction conditions: **1a** (3 mmol), LiClO₄ (3 mmol), B₂pin₂ (6 mmol), Cs₂CO₃ (3 mmol), MeOH (30 mL), 20 °C. *L*-type glassy carbon as working electrode, Pt wire as counter electrode and saturated calomel electrode (SCE) as reference. Scan rate: 0.02 V/s.

According to our mechanistic investigations and recent relevant literatures,^[21] a plausible mechanism for this electrochemical borylation of aryl iodides is proposed (Scheme 2). Initially, at the cathode, aryl iodide **1** undergoes reduction to afford the corresponding radical anion **C**, which is further transformed into the aryl radical **D** *via* carbon—halogen bond cleavage. Further, aryl radical **D** interacts with B_2pin_2 in the presence of a base (RO⁻) to generate the desired product **3** along with the formation of **G** through intermediate **E** and **F**. Meanwhile, the reaction becomes redox neutral due to the anodic oxidation of the solvent to give oxides which balance the overall transformation. Consequently, intermediate **G** is quenched by solvent, oxides or other aryl iodides *via* SET to afford **E**. However, the possibility of the formation of desired product **3** *via* the generation of boron-centered radical **I** cannot be ruled out at this stage.

Scheme 2 Proposed mechanism



Conclusions

In summary, we have developed a sustainable and practical electrochemical borylation of aryl iodides, providing a very useful approach to arylboronic esters. EPR, CV and PVD experiments verified the formation of aryl radicals in this electrochemical borylation reaction, which supports a radical borylation mechanism. This electrochemical borylation reaction is complementary to other borylation methods and might inspire further investigations in the radical borylation strategy.

Experimental

An undivided cell was equipped with two platinum mesh electrodes and connected to a DC regulated power supply. Aryl iodide **1** (0.5 mmol), B_2pin_2 (2 mmol, 508 mg, 4 equiv.), Cs_2CO_3 (1.0 mmol, 326 mg, 2 equiv.) and 5 mL of anhydrous MeOH were added to the cell. The mixture was electrolyzed using constant current conditions (13 mA) at 65 °C under magnetic stirring. After almost 3 h, the TLC analysis indicated that the electrolysis was complete (witnessed by the disappearance of the aryl iodide). Upon cooling to room temperature, the reaction mixture was transferred to a 100 mL flask by methanol, and then a little silica gel was added into it. After removal of the solvent *in vacuo*, the residue was poured onto a silica gel column and purified by column chromatography to give the desired product **3**.

Supporting Information

The supporting information for this article is available on the WWW under https://doi.org/10.1002/cjoc.201900001.

Acknowledgement

The project was supported by the National Natural Science Foundation of China (Grant No. 21772003). We also thank the "1000-Youth Talents Plan" and Peking University for start-up funds. This work was also partially funded by the Peking University carbon capture, utilization and storage project supported by BHP Billiton.

References

 (a) Suzuki, A. Organoborates in new synthetic reactions. Acc. Chem. Res. 1982, 15, 178–184; (b) Miyaura, N.; Suzuki, A. Palladium-Catalyzed Cross-Coupling Reactions of Organoboron Compounds. Chem. *Rev.* **1995**, *95*, 2457–2483; (c) Xu, L.; Zhang, S.; Li, P. Boron-selective reactions as powerful tools for modular synthesis of diverse complex molecules. *Chem. Soc. Rev.* **2015**, *44*, 8848–8858.

- [2] (a) Brown, H. C.; Cole, T. E. Organoboranes. 31. A simple preparation of boronic esters from organolithium reagents and selected trialkoxyboranes. *Organometallics* **1983**, *2*, 1316–1319; (b) Brown, H. C.; Srebnik, M.; Cole, T. E. Organoboranes. 48. Improved procedures for the preparation of boronic and borinic esters. *Organometallics* **1986**, *5*, 2300–2303.
- [3] Chow, W. K.; Yuen, O. Y.; Choy, P. Y.; So, C. M.; Lau, C. P.; Wong, W. T.; Kwong, F. Y. A decade advancement of transition metal-catalyzed borylation of aryl halides and sulfonates. *RSC Adv.* **2013**, *3*, 12518–12539.
- [4] (a) Giroux, A.; Han, Y.; Prasit, P. One pot biaryl synthesis via *in situ* boronate formation. *Tetrahedron Lett.* **1997**, *38*, 3841–3844; (b) Ishiyama, T.; Murata, M.; Miyaura, N. Palladium(0)-Catalyzed Cross-Coupling Reaction of Alkoxydiboron with Haloarenes: A Direct Procedure for Arylboronic Esters. *J. Org. Chem.* **1995**, *60*, 7508–7510; (c) Lipshutz, B. H.; Moser, R.; Voigtritter, K. R. Miyaura Borylations of Aryl Bromides in Water at Room Temperature. *Isr. J. Chem.* **2010**, *50*, 691–695; (d) Tempest, P. A.; Armstrong, R. W. Cyclobutenedione Derivatives on Solid Support: Toward Multiple Core Structure Libraries. *J. Am. Chem. Soc.* **1997**, *119*, 7607–7608.
- [5] (a) Liu, X.-W.; Echavarren, J.; Zarate, C.; Martin, R. Ni-Catalyzed Borylation of Aryl Fluorides via C–F Cleavage. J. Am. Chem. Soc. 2015, 137, 12470–12473; (b) Moldoveanu, C.; Wilson, D. A.; Wilson, C. J.; Leowanawat, P.; Resmerita, A.-M.; Liu, C.; Rosen, B. M.; Percec, V. Neopentylglycolborylation of ortho-Substituted Aryl Halides Catalyzed by NiCl₂-Based Mixed-Ligand Systems. J. Org. Chem. 2010, 75, 5438–5452; (c) Yamamoto, T.; Morita, T.; Takagi, J.; Yamakawa, T. NiCl₂(PMe₃)₂-Catalyzed Borylation of Aryl Chlorides. Org. Lett. 2011, 13, 5766–5769.
- [6] (a) Zhu, W.; Ma, D. Formation of Arylboronates by a Cul-Catalyzed Coupling Reaction of Pinacolborane with Aryl Iodides at Room Temperature. Org. Lett. 2006, 8, 261–263; (b) Guobing, Y.; Yang, M.; Jian, Y. Ligand-Free Copper-Catalyzed Borylation of Aryl and Benzyl Halides with Bis(pinacolato)diboron. Lett. Org. Chem. 2012, 9, 71–75; (c) Kleeberg, C.; Dang, L.; Lin, Z.; Marder, T. B. A Facile Route to Aryl Boronates: Room-Temperature, Copper-Catalyzed Borylation of Aryl Halides with Alkoxy Diboron Reagents. Angew. Chem. Int. Ed. 2009, 48, 5350–5354.
- [7] Bose, S. K.; Deißenberger, A.; Eichhorn, A.; Steel, P. G.; Lin, Z.; Marder, T. B. Zinc-Catalyzed Dual C–X and C–H Borylation of Aryl Halides. *Angew. Chem. Int. Ed.* **2015**, *54*, 11843–11847.
- [8] Bedford, R. B.; Brenner, P. B.; Carter, E.; Gallagher, T.; Murphy, D. M.; Pye, D. R. Iron-Catalyzed Borylation of Alkyl, Allyl, and Aryl Halides: Isolation of an Iron(I) Boryl Complex. *Organometallics* **2014**, *33*, 5940–5943.
- [9] (a) Moeller, K. D. Synthetic applications of anodic electrochemistry. Tetrahedron 2000, 56, 9527-9554; (b) Sperry, J. B.; Wright, D. L. The application of cathodic reductions and anodic oxidations in the synthesis of complex molecules. Chem. Soc. Rev. 2006, 35, 605-621; (c) Jutand, A. Contribution of electrochemistry to organometallic catalysis. Chem. Rev. 2008, 108, 2300-2347; (d) Yoshida, J.-i.; Kataoka, K.; Horcajada, R.; Nagaki, A. Modern strategies in electroorganic synthesis. Chem. Rev. 2008, 108, 2265-2299; (e) Francke, R.; Little, R. D. Redox catalysis in organic electrosynthesis: basic principles and recent developments. Chem. Soc. Rev. 2014, 43, 2492-2521; (f) Horn, E. J.; Rosen, B. R.; Baran, P. S. Synthetic organic electrochemistry: An enabling and innately sustainable method. ACS Cent. Sci. 2016, 2, 302-308; (g) Feng, R.; Smith, J. A.; Moeller, K. D. Anodic Cyclization Reactions and the Mechanistic Strategies That Enable Optimization. Acc. Chem. Res. 2017, 50, 2346-2352; (h) Jiang, Y.; Xu, K.; Zeng, C. Use of Electrochemistry in the Synthesis of Heterocyclic Structures. Chem. Rev. 2018, 118, 4485-4540; (i) Yan, M.; Kawamata, Y.; Baran, P. S. Synthetic Organic Electrochemical Methods Since 2000: On the Verge of a Renaissance. Chem. Rev. 2017, 117, 13230-13319; (j) Ma,

C.; Fang, P.; Mei, T.-S. Recent Advances in C-H Functionalization Using Electrochemical Transition Metal Catalysis. ACS Catal. 2018, 8, 7179–7189; (k) Möhle, S.; Zirbes, M.; Rodrigo, E.; Gieshoff, T.; Wiebe, A.; Waldvogel, S. R. Modern Electrochemical Aspects for the Synthesis of Value-Added Organic Products. Angew. Chem. Int. Ed. 2018, 57, 6018-6041; (I) Sauer, G. S.; Lin, S. An Electrocatalytic Approach to the Radical Difunctionalization of Alkenes. ACS Catal. 2018, 8, 5175-5187; (m) Sauermann, N.; Meyer, T. H.; Qiu, Y.; Ackermann, L. Electrocatalytic C-H Activation. ACS Catal. 2018, 8, 7086-7103; (n) Tang, S.; Liu, Y.; Lei, A. Electrochemical Oxidative Cross-coupling with Hydrogen Evolution: A Green and Sustainable Way for Bond Formation. Chem 2018, 4, 27-45; (o) Waldvogel, S. R.; Lips, S.; Selt, M.; Riehl, B.; Kampf, C. J. Electrochemical Arvlation Reaction. Chem. Rev. 2018. 118, 6706-6765; (p) Wiebe, A.; Gieshoff, T.; Möhle, S.; Rodrigo, E.; Zirbes, M.; Waldvogel, S. R. Electrifying Organic Synthesis. Angew. Chem. Int. Ed. 2018, 57, 5594-5619; (q) Yoshida, J.-i.; Shimizu, A.; Havashi, R. Electrogenerated Cationic Reactive Intermediates: The Pool Method and Further Advances. Chem. Rev. 2018, 118, 4702-4730; (r) Yang, Q.-L.; Fang, P.; Mei, T.-S. Recent Advances in Organic Electrochemical C-H Functionalization. Chin. J. Chem. 2018, 36, 338-352; (s) Hou, Z.-W.; Yan, H.; Song, J.-S.; Xu, H.-C. Electrochemical Synthesis of (Aza)indolines via Dehydrogenative [3+2] Annulation: Application to Total Synthesis of (±)-Hinckdentine A. Chin. J. Chem. 2018, 36, 909-915; (t) Shao, A.; Li, N.; Gao, Y.; Zhan, J.; Chiang, C.-W.; Lei, A. Electrochemical Intramolecular C-H/O-H Cross-Coupling of 2-Arylbenzoic Acids. Chin. J. Chem. 2018, 36, 619-624.

- [10] (a) Liu, Q.; Sun, B.; Liu, Z.; Kao, Y.; Dong, B.-W.; Jiang, S.-D.; Li, F.; Liu, G.; Yang, Y.; Mo, F. A general electrochemical strategy for the Sandmeyer reaction. *Chem. Sci.* 2018, *9*, 8731–8737; (b) Zhang, L.; Zhang, Z.; Hong, J.; Yu, J.; Zhang, J.; Mo, F. Oxidant-Free C(sp²)–H Functionalization/C–O Bond Formation: A Kolbe Oxidative Cyclization Process. *J. Org. Chem.* 2018, *83*, 3200–3207; (c) Zhang, L.; Zhang, J.; Li, K.; Mo, F. Oxidant-free oxidation of C–H bonds by cathodic hydrogen evolution: a phosphonic Kolbe oxidation/cyclization process. *Green Chem.* 2018, *20*, 3916–3920.
- [11] Gennaro, A.; Isse, A. A.; Mussini, P. R. Activation of the Carbon– Halogen Bond. In Organic Electrochemistry: Revised and Expanded Fifth Edition, Eds.: Hammerich, O.; Speiser, B., Taylor & Francis Group, Boca Raton, 2015.
- [12] (a) Chen, K.; Wang, L.; Meng, G.; Li, P. Recent Advances in Transition-Metal-Free Aryl C–B Bond Formation. *Synthesis* 2017, 49, 4719–4730; (b) Mo, F.; Qiu, D.; Zhang, Y.; Wang, J. Renaissance of Sandmeyer-Type Reactions: Conversion of Aromatic C–N Bonds into C–X Bonds (X = B, Sn, P, or CF₃). *Acc. Chem. Res.* 2018, *51*, 496–506; (c) Yan, G.; Huang, D.; Wu, X. Recent Advances in C–B Bond Formation through a Free Radical Pathway. *Adv. Synth. Catal.* 2018, *360*, 1040–1053.
- [13] (a) Mo, F.; Jiang, Y.; Qiu, D.; Zhang, Y.; Wang, J. Direct Conversion of Arylamines to Pinacol Boronates: A Metal-Free Borylation Process. *Angew. Chem. Int. Ed.* 2010, *49*, 1846–1849; (b) Qiu, D.; Jin, L.; Zheng, Z.; Meng, H.; Mo, F.; Wang, X.; Zhang, Y.; Wang, J. Synthesis of Pinacol Arylboronates from Aromatic Amines: A Metal-Free Transformation. *J. Org. Chem.* 2013, *78*, 1923–1933; (c) Qiu, D.; Zhang, Y.; Wang, J. Direct synthesis of arylboronic pinacol esters from arylamines. *Org. Chem. Front.* 2014, *1*, 422–425.
- [14] (a) Yu, J.; Zhang, L.; Yan, G. Metal-Free, Visible Light-Induced Borylation of Aryldiazonium Salts: A Simple and Green Synthetic Route to

Arylboronates. *Adv. Synth. Catal.* **2012**, *354*, 2625–2628; (b) Zhu, C.; Yamane, M. Transition-Metal-Free Borylation of Aryltriazene Mediated by BF₃·OEt₂. *Org. Lett.* **2012**, *14*, 4560–4563; (c) Erb, W.; Albini, M.; Rouden, J.; Blanchet, J. Sequential One-Pot Access to Molecular Diversity through Aniline Aqueous Borylation. *J. Org. Chem.* **2014**, *79*, 10568–10580; (d) Zhao, C.-J.; Xue, D.; Jia, Z.-H.; Wang, C.; Xiao, J. Methanol-Promoted Borylation of Arylamines: A Simple and Green Synthetic Method to Arylboronic Acids and Arylboronates. *Synlett* **2014**, *25*, 1577–1584.

- [15] (a) Chen, K.; Zhang, S.; He, P.; Li, P. Efficient metal-free photochemical borylation of aryl halides under batch and continuous-flow conditions. Chem. Sci. 2016, 7, 3676-3680; (b) Mfuh, A. M.; Doyle, J. D.; Chhetri, B.; Arman, H. D.; Larionov, O. V. Scalable, Metal- and Additive-Free, Photoinduced Borylation of Haloarenes and Quaternary Arylammonium Salts. J. Am. Chem. Soc. 2016, 138, 2985-2988; (c) Mfuh, A. M.; Schneider, B. D.; Cruces, W.; Larionov, O. V. Metal- and additive-free photoinduced borvlation of haloarenes. Nature Protocols 2017, 12, 604; (d) Pinet, S.; Liautard, V.; Debiais, M.; Pucheault, M. Radical Metal-Free Borylation of Aryl Iodides. Synthesis 2017, 49, 4759–4768; (e) Zhang, J.; Wu, H.-H.; Zhang, J. Cesium Carbonate Mediated Borylation of Aryl Iodides with Diboron in Methanol. Eur. J. Org. Chem. 2013, 2013, 6263-6266; (f) Zhang, L.; Jiao, L. Pyridine-Catalyzed Radical Borylation of Aryl Halides. J. Am. Chem. Soc. 2017, 139, 607-610; (g) Liu, W.; Yang, X.; Gao, Y.; Li, C.-J. Simple and Efficient Generation of Aryl Radicals from Aryl Triflates: Synthesis of Aryl Boronates and Aryl Iodides at Room Temperature. J. Am. Chem. Soc. 2017, 139, 8621-8627.
- [16] Candish, L.; Teders, M.; Glorius, F. Transition-Metal-Free, Visible-Light-Enabled Decarboxylative Borylation of Aryl N-Hydroxyphthalimide Esters. J. Am. Chem. Soc. 2017, 139, 7440–7443.
- [17] Buettner, G. R. Spin Trapping: ESR parameters of spin adducts 1474 1528V. Free Radic. Biol. Med. 1987, 3, 259–303.
- [18] (a) Augusto, O.; Kunze, K. L.; Ortiz de Montellano, P. R. N-Phenylprotoporphyrin IX formation in the hemoglobin-phenylhydrazine reaction. Evidence for a protein-stabilized iron-phenyl intermediate. J. Biol. Chem. 1982, 257, 6231–6241; (b) Hill, H. A. O.; Thornalley, P. J. Phenyl radical production during the oxidation of phenylhydrazine and in phenylphydrazine-induced haemolysis. Febs. Lett. 1981, 125, 235–238.
- [19] Janzen, E. G.; Liu, J. I. P. Radical addition reactions of 5,5-dimethyl-1-pyrroline-1-oxide. ESR spin trapping with a cyclic nitrone. *J. Magn. Reson.* (1969) **1973**, 9, 510–512.
- [20] Marriott, P. R.; Perkins, M. J.; Griller, D. Spin trapping for hydroxyl in water: a kinetic evaluation of two popular traps. *Can. J. Chem.* **1980**, *58*, 803–807.
- [21] (a) Cheng, Y.; Mück-Lichtenfeld, C.; Studer, A. Transition Metal-Free 1,2-Carboboration of Unactivated Alkenes. J. Am. Chem. Soc. 2018, 140, 6221–6225; (b) Cheng, Y.; Mück-Lichtenfeld, C.; Studer, A. Metal-Free Radical Borylation of Alkyl and Aryl Iodides. Angew. Chem. Int. Ed. 2018, 57, 16832–16836.

Manuscript received: January 1, 2019 Manuscript revised: January 26, 2019 Manuscript accepted: January 30, 2019 Accepted manuscript online: February 4, 2019 Version of record online: February 26, 2019