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Electrochemical Fluorination of Vinyl Boronates through Donor-Stabilized Vinyl Carbocation Intermediates

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Abstract

The electrochemical generation of vinyl carbocations from alkenyl boronic esters and boronates is reported. Using easy-to-handle nucleophilic fluoride reagents, these intermediates are trapped to form fully substituted vinyl fluorides. Mechanistic studies support the formation of dicoordinated carbocations through sequential single-electron oxidation events. Notably, this electrochemical fluorination features fast reaction times and Lewis acid-free conditions. This transformation provides a complementary method to access vinyl fluorides with simple fluoride salts such as TBAF.

Graphical Abstract

· *Electrochemical generation of vinyl carbocations*   · *Lewis-acid free*
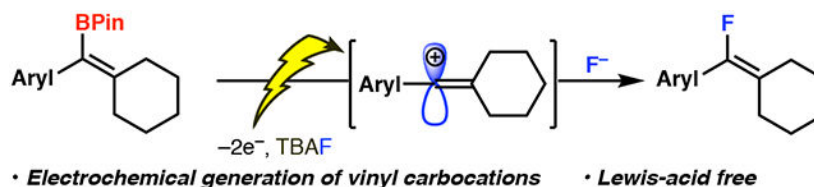
Vinyl carbocations were generated via single-electron oxidation of vinyl boronates using electrical potentials. This electrochemical process enabled the formation of these reactive species without the use of Lewis or Brønsted acids. The intermediate vinyl carbocations were trapped with nucelophilic fluoride sources to yield vinyl fluorides; the production of new C—C, C—Cl, and C—Br bonds was also demonstrated.

Keywords

vinyl carbocations; fluorination; electrochemistry; alkenyl boronates; vinyl fluorides

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Carbocations, a common synthon in synthetic organic chemistry logic, have been studied for more than 100 years.[1] While the reactivities and properties of alkyl carbocations have been the main focus of these studies, highly reactive vinyl carbocations and their ensuing bond-forming reactions have been the subject of far fewer research efforts. Nonetheless, vinyl cations have been isolated and characterized in the solid state[2a,b], revealing their remarkable linear geometry, and have been generated by a variety of conditions including solvolysis[2c], photolysis[2d-f], leaving group abstraction[2g-j], and alkyne protonation/transition metal-activation[2k,l]. With the exceptions of photolysis, which requires high-energy UV light, and solvolysis, which requires high temperatures, vinyl cation generation often relies on potent Lewis or Brønsted acids that can be poisoned by heteroatoms and requires rigorous air-free handling. At the outset of the current study, we hypothesized that these reactive intermediates could instead be generated *via* consecutive single-electron oxidation events, analogous to the Hofer-Moest electrochemical oxidation of alkyl carboxylates to alkyl carbocations (Scheme 1a).[3a,b] Electrochemical oxidation has become a powerful strategy to generate a variety of reactive cationic intermediates, as is demonstrated in the cation pool method.[3c,d] This unconventional approach to generating these high-energy species could allow for milder and less stringent reaction conditions, perhaps enabling the discovery of new chemical transformations. Here, we report our initial studies in this area, where alkenyl boronates are converted to vinyl fluorides electrochemically through nucleophilic trapping of vinyl carbocation intermediates (Scheme 1b). While vinyl fluorides have well established syntheses, including but not limited to Wittig olefination reactions, addition to alkynes and allenes, and transition metal-catalyzed cross-coupling reactions, we believe this report serves as a complementary and potentially divergent method to gain access to a variety of vinyl halides as well as other olefinic products due to the vinyl carbocation generated.[4]

Inspired by the Hofer-Moest oxidation and reports of generation of alkyl carbocations from redox-active esters,[3,5] attempts at oxidation of carboxylate derivatives by means of various photochemical, electrochemical, and chemical processes provided intractable mixtures of products that gave no evidence for vinyl carbocation formation.[6] We turned to other redox active groups, particularly trifluoroborates, (Table 1) since these are known to undergo single electron oxidation.[7] We were gratified to find that electrolysis in an undivided cell of vinyl trifluoroborate **1** with a platinum cathode and carbon anode at a constant working potential of +1.8V *vs* SCE in dichloromethane (DCM) with tetrabutylammonium fluoride trihydrate (TBAF) as a trapping agent produced vinyl fluoride **2** in 42% yield by ^{19}F NMR (Table 1, entry 1) after only 15 minutes. The styrenyl position was key for reactivity, as non-styrenyl boronates were not competent for this transformation.[6] In this solvent, however, the vinyl chloride product was also observed in 20% yield by ^1H NMR, presumably from reduction of DCM to produce the chloride anion. Switching the solvent to tetrahydrofuran (THF) or dimethylformamide (DMF) (entries 2,3) led to trace or no product respectively; ultimately use of acetonitrile (MeCN) yielded vinyl fluoride **2** in 65% isolated yield with no vinyl chloride impurity (entry 4). We also examined vinyl pinacol boronate **3**, as more electron-rich boronates have been demonstrated to have a profound effect on the oxidation potential of the substrate.[8] Pinacol boronate (BPinF) **3** was generated *in situ* from the starting pinacol boronic ester: ^{11}B NMR studies indicated that the boronate was fully formed in solution with 3 equivalents of TBAF.[6] We believe the anionic boronate complex to be the

redox active intermediate, as without this fluoride additive no reaction occurs. Subjecting this pinacol boronate (**3**) to the reaction conditions yielded vinyl fluoride **2** in a slightly increased 70% isolated yield (entry 5). Other electrolytes, fluoride sources, and equivalents of TBAF led to diminished yield (entries 6–12). The remaining mass balance for these reactions are ketone and enone products, the latter presumably arising from oxidation of the ketone, which we attribute to water quenching of a vinyl carbocation intermediate.[6] It is noteworthy that this reaction does not need to be carried out under rigorously anhydrous conditions, likely due to the high nucleophilicity of the fluoride anion. We believe water to serve as the sacrificial oxidant, and attempts to perform the reaction under water-free conditions resulted in incomplete conversion of the starting material (entry 13). Importantly, we found that analogous conditions could be used to produce vinyl chloride **4** and bromide **5** simply by substituting TBAF with TBACl or TBABr (entries 14,15).[6]

With these results in hand, we began to explore the scope of this reaction. Initial efforts focused on utilizing electron-rich arenes, such as the *p*-anisole substituent of boronate **3**, that would stabilize putative carbocation intermediates. Strongly electron-donating substituents produced vinyl fluorides **6–9** in 50–82% yield (Scheme 2). Vinyl fluoride **7** was also isolated in good yield utilizing only three equivalents of TBAF on 1 mmol scale. Alkenyl boronic esters bearing *meta* substituents and an *ortho* or *para* donor were also tolerated, yielding vinyl fluorides **10** and **11** in 59% and 47% yield respectively. Additionally, novel fluoro-analogue **12** of chlorotrianisene, a nonsteroidal estrogen[9a], was generated in 60% yield. Other appended ring sizes and alkyl chains also led to production of the vinyl fluoride (**13–16**). Constant voltage conditions were key to produce electron–rich aniline fluoride product **16.**

Less electron-donating substituents were tolerated, but led to incomplete conversion even at higher applied potentials (**17–19**). Notably, these N—H containing compounds are not tolerated under routine Lewis acid promoted vinyl carbocation formation, but are commonly seen in natural products and drug molecules.[2,9b] The boronic ester bearing a simple phenyl ring did not lead to formation of vinyl fluoride **20**, even under forcing conditions.

Throughout these studies we observed that only electron-rich arenes were competent in this transformation. Yields increased with decreasing Hammet σ_p parameter, suggesting that there was a carbocation formed at the carbon once bearing the boronic ester. The trend of decreasing yield, **6>13>17>19**, with corresponding σ_p values of −0.81<−0.27<−0.17<0.00 for the respective *para* donor substituents, was observed.[10] Additionally, if a *meta*-methoxy group were present on the arene, an electron-*withdrawing* substituent with σ_m=+0.12, **21** was not formed.[6,10] This trend suggested the formation of a carbocation intermediate, and so we carried out further mechanistic studies to investigate the intermediacy of a vinyl carbocation.

First we probed for canonical vinyl carbocation reactivity. One classic mode of reactivity of vinyl carbocations is E1 elimination to form alkyne products.[11] Upon subjection of alkenyl boronic ester **22** to the reaction conditions, alkyne **23**, the product of E1 elimination of putative vinyl carbocation **24**, was observed in moderate yield (Scheme 3a). A similar

elimination occurs with trisubstituted alkenyl boronic esters to yield alkyne.[6] This does however limit the substrates for fluorination to tetrasubstituted alkenyl boronates.

In order to rule out production of this alkyne from a vinyl fluoride intermediate, styrenyl fluoride **25** was prepared and subjected to the reaction conditions. No conversion to the alkyne was observed and the starting material was recovered in quantitative yield.

To probe the intermediacy of a linear vinyl carbocation intermediate, unsymmetric alkenyl boronic ester **26** was prepared as a single isomer. Subjection of this material to the reaction conditions yielded a mixture of *Z:E* vinyl fluoride products **26** in a 6.25:1 ratio (Scheme 3b). This supports fluoride nucleophilic attack of a linear intermediate as opposed to other stereo retentive pathways.

Vinyl carbocations are also known to undergo C—C bond forming reactions with arene nucleophiles.[2,11] To explore Friedel-Crafts reactivity, **1** was subjected to the reaction conditions in the presence of 10 equivalents of electron rich N-Me pyrrole instead of TBAF. Pyrrole nucleophiles have been observed to trap similar *p*-anisole substituted vinyl carbocations generated by photolysis.[2d] In the event, arylated products **28** were produced in a 2.7:1 ratio in 48% yield (Scheme 3c). This product ratio further supports a vinyl carbocation intermediate as opposed to a radical intermediate, as such radical additions are reported to exclusively form C2 addition products.[12]

C—C bond forming reactions *via* intramolecular C—H insertion reactions have also been observed in several studies of vinyl carbocations.[3g–k] In order to probe for this type of reactivity, the trifluoroborate salt **29** with appended alkyl chains was prepared and subjected to electrolysis in a divided cell. In the presence of fluoride these products were not observed, and so the pre-activated trifluoroborate was used. Gratifyingly, we observed production of the C—H insertion products **30** as a mixture of olefin isomers, albeit in low yield (Scheme 3d). This diminished yield is due to the subsequent decomposition of the electron-rich tetrasubstituted styrene products under the oxidative conditions.[6]

To further investigate the mechanistic pathway to the proposed vinyl carbocation we performed cyclic voltammetry experiments. The tetrabutylammonium salt of **1** showed two irreversible oxidative events at +1.12 V and +1.56 V *vs* SCE (Scheme 4a).[6] This experiment demonstrated evidence for a two-electron oxidation process; additionally, bulk electrolysis coulometry at a constant potential of 1.8 V *vs* SCE further confirmed this with a calculated Faradaic efficiency for two-electrons per boronate substrate of 73%.[6] We hypothesized that the initial oxidation would yield a vinyl radical, as is proposed for the oxidation of a variety of alkyl trifluoroborates.[13] In order to probe for this intermediate, trifluoroborate **1** was subjected to the reaction conditions in the presence of deuterated H/D-atom donor propane thiol (Scheme 4b). Deuterium incorporation exclusively at the styrene position (**31**) was observed supporting the intermediacy of a vinyl radical. To determine if this radical intermediate was generated at the lower potential, trifluoroborate **1** was subjected to constant voltage electrolysis in the presence of N-methyl pyrrole at +1.1 V *vs* SCE (Scheme 4c). At this potential different regioselectivity was observed compared to at +1.8 V (Scheme 3b); only the C2 arylation product was observed suggesting the presence of a radical.[12]

Furthermore, at this lower potential no vinyl fluoride products were observed in the presence of TBAF.[5]

With these combined experiments supporting the intermediacy of a vinyl radical after the first oxidation at +1.1 V *vs* SCE, we propose the sequential ECE-type oxidation mechanism in Scheme 5. DFT calculations were performed to further understand the initial oxidation event. Initial *in silico* oxidation of the calculated HOMO of trifluoroborate anion **32** yielded delocalized radical cation **33**, in good agreement with experimental data at a calculated potential of +1.04 V *vs* SCE (Scheme 5a). We propose that this can subsequently eliminate BF_3 to yield vinyl radical **34** that undergoes a second oxidation to yield vinyl carbocation **35** (Scheme 5b). In the case of the pinacol boronic esters, an equivalent of BPin─F is produced that was observed by ^{19}F and ^{11}B NMR.[6] This carbocation intermediate can be trapped by nucleophilic fluoride in solution to furnish vinyl fluoride product **2**.

In conclusion, we report the novel generation of vinyl carbocations *via* an electrochemical potential; from a synthetic standpoint the products of these reactions have potential application in medicinal chemistry. Vinyl fluorides have been demonstrated to be effective enol mimics,[14] are considered bioisosteres of the peptide bond,[15] and fluorinated drug compounds can often display exquisite pharmacokinetic properties and binding affinity compared to the parent C─H containing compound.[16] While there are several reports of conversion of aryl boronates to aryl fluorides, these reaction conditions commonly rely on the use electrophilic fluorine reagents and silver salts.[17] The use of easy-to-handle nucleophilic fluoride reagents has recently been reported for generation of aryl fluorides from aryl boronates, but there are few examples of the conversion of alkenyl boronates to vinyl fluorides.[17,18] Moreover, vinyl fluorides are often synthesized from alkynes, yielding di- or trisubstituted alkene products, while methods to access fully substituted vinyl fluorides typically require prefunctionalized fluorination reagents.[4,19,20] This electrochemical method features short reaction times in moderate to good yield. Additionally, mechanistic studies support the intermediacy of a vinyl radical followed by a second oxidation to a vinyl cation; this evidence suggests that electrochemical oxidation may be a viable strategy to access dicoordinate vinyl carbocations, emerging intermediates in organic synthesis.[21]

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgements

References

[1]. [a]Olah GAJ. Org. Chem 2001, 66, 5943–5957. [PubMed: 11529717] [b]Naredla RR, Klumpp DA, Chem. Rev 2013, 113, 6905–6948. [PubMed: 23819438]

[2]. [a]Müller T, Juhasz M, Reed CA, Angew. Chem 2004, 116, 1569–1572;Angew. Chem. Int. Ed 2004, 43, 1543–1546.[b]Bismuto A, Nichol GS, Duarte F, Cowley MJ, Thomas S, Angew. Chem 2020, 132, 12831–12835;Angew. Chem. Int. Ed 2020, 59, 12731–12735.[c]Pfeifer WD, Bahn CA, Schleyer P. v. R., Bocher S, Harding EC, Hummel K, Hanack M, Stang PJJ. Am. Chem. Soc 1971, 93, 1513–1516.[d]Byrne PA, Kobayashi S, Wüthwein E–U, Ammer J, Mayr H, J. Am. Chem. Soc 2017, 139, 1499–1511. [PubMed: 28040896] [e]Kitamura T, Kobayashi S, Taniguchi H, J. Org. Chem 1982, 47, 2323–2328.[f]Slegt M, Grohnheid R, van der Vlugt D, Ochiai M, Okuyama T, Zuilhof H, Overkleeft HS, Loder G J. Org. Chem 2006, 71, 2227–2235. [PubMed: 16526767] [g]Biermann U, Koch R, Metzger JO, Angew. Chem 2006, 118, 3146–3150;Angew. Chem. Int. Ed 2006, 45, 3076–3079.[h]Cleary SE, Hensinger J, Brewer M, Chem. Sci 2017, 8, 6810–6814. [PubMed: 29147505] [i]Popov S, Shao B, Bagdasarian AL, Benton TR, Zou L, Yang Z, Houk KN, Nelson HM, Science 2018, 361, 381–387. [PubMed: 30049877] [j]Wigman B, Popov S, Bagdasarian AL, Shao B, Benton TR, Fisher SP, Lavallo V, Houk KN, Nelson HM, J. Am. Chem. Soc 2019, 141, 9140–9144. [PubMed: 31082208] [k]Zhang F, Das S, Walkinshaw AJ, Casitas A, Taylor M, Suero MG, Gaunt MJ, J. Am. Chem. Soc 2014, 136, 8851–8854. [PubMed: 24905079] [l]Schroeder S, Strauch C, Gaelings N, Niggemann M, Angew. Chem 2019, 131, 5173–5177;Angew. Chem., Int. Ed 2019, 58, 5119–5123.

[3]. [a]Hofer H, Moest M, Justus Liebigs Ann. Chem 1902, 323, 284–323.[b]Corey EJ, Bauld NL, La Londe RT, Casanova J Jr., Kaiser ET, J. Am. Chem. Soc 1960, 82, 2645–2646.[c]Yoshida J–I, Shimizu A, Hayashi R, Chem. Rev 2018, 118, 4702–4730. [PubMed: 29077393] [d]Okajima M, Soga K, Nokami T, Suga S, Yoshida J–I, Org. Lett 2006, 8, 5005–5007. [PubMed: 17048829]

[4]. Examples of tetrasubstituted vinyl fluoride syntheses: [a] Lei XS, Lei, Dutheuil G, Pannecoucke X, Quirion JC, Org. Lett 2004, 6, 2101–2104. [PubMed: 15200295] [b]Pomeisl K, Cejka J, Kvicala J, Paleta O, Eur. J. Org. Chem 2007, 37, 5917–5925.[c]Van der Veken P, Kertesz I, Senten K, Haemers A, Augustyns K, Tetrahedron Lett. 2003, 44, 6231–6234.[d]Zapata AJ, Gu YH, Hammond GB, J. Org. Chem 2000, 65, 227–234. [PubMed: 10813920] [e]Chevrie D, Lequeux T, Demoute JP, Pazenok S, Tetrahedron Lett. 2003, 44, 8127–8130.[e]Zhu LG, Ni CF, Zhao YC, Hu JB, Tetrahedron, 2010, 66, 5089–5100.[f]Ghosh AK, Banerjee S, Sinha S, Kang SB, Zajc B, J. Org. Chem 2009, 74, 3689–3697. [PubMed: 19361189] [g]Lin J, Welch JT, Tetrahedron Lett. 1998, 39, 9613–9616.[h]Yoshimatsu M, Murase Y, Itoh A, Tanabe G, Muraoka O, Chem. Lett 2005, 34, 998–999.[i]Usuki Y, Iwaoka M, Tomoda S, J. Chem. Soc., Chem. Commun 1992, 16, 1148–1150.[k]Sano K, Fukuhara T, Hara S, J. Fluorine Chem 2009, 130, 708–713.[l]Dolensky B, Kirk KL, J. Org. Chem 2002, 67, 3468–3473. [PubMed: 12003561] [m]Landelle G, Champagne PA, Barbeau X, Paquin J-F, Org. Lett 2009, 11, 681–684. [PubMed: 19143558] [n]Dutheuil G, Couve-Bonnaire S, Pannecoucke X, Tetrahedron, 2009, 65, 6034–6038.[o]Luo HQ, Hu XH, Loh T-P, Tetrahedron Lett. 2010, 51, 1041–1043.[p]for an in depth review see: Landelle G, Bergeron M, Turcotte-Savard M–O, Paquin J–F, Chem. Soc. Rev 2011, 40, 2867–2908. [PubMed: 21399789]

[5]. Webb EW, Park JB, Cole EL, Donnelly DJ, Bonacorsi SJ, Ewing WR, Doyle AG, J. Am. Chem. Soc 2020, 142, 9493–9500. [PubMed: 32378889]

[6]. See supporting information for details.

[7]. [a]Suzuki J, Tanigawa M, Inagi S, Fuchigami T, ChemElectroChem 2016 3, 2078–2083.[b]H Morris J, Gysling HJ, Reed D Chem. Rev 1985, 85, 51–76.[c]Molander GA, Colombel V, Braz V, Org. Lett 2011, 13, 1852–1855. [PubMed: 21391555] [d]Neufeldt SR, Seigerman CK, Sanford MS, Org. Lett 2013, 15, 2302–2305. [PubMed: 23597105] [e]Lee HG, Chung TD, Go SY, Chung H, Shin SJ, An S, Youn JH, Im TY, Kim JY, 2021 ChemRxiv preprint DOI: 10.33774/chemrxiv-2021-bvf1l

[8]. Lennox AJJ, Nutting JE, Stahl SS, Chem. Sci 2018, 9, 356–361. [PubMed: 29732109]

[9]. [a]Luniwal A, Jetson R, Erhardt P, Analgoue-based drug discovery. Wiley, Hoboken, 2012, p. 165–185.[b]Kerru N, Hummidi L, Maddila S, Gangu KK, Jonnalagadda SB Molecules 2020, 25, 1909.

[10]. Hansch C, Leo A, Taft RW, Chem. Rev 1991, 91, 165–195. (Note: σ_p value for ─SMe and ─NHCO$_2$Me substituents used).$_{p2}$

[11]. [a]Stang PJ, Rappoport Z, Hanack M, Subramanian LR, Vinyl Cations, Academic Press, New York, 1979, p. 68–76.[b]Rappoport Z, Shulman P, Thuval M, J. Am. Chem. Soc 1978, 100, 7041–7051.

[12]. [a]Kocao lu E, Karaman MA, Tokogöz H, Talaz O, ACS Omega, 2017 2, 5000–5004. [PubMed: 31457776] [b]Li Z, Gandon V, Bour C, Chem. Comm 2020, 56, 6507–6510. [PubMed: 32396586] [c]Suleymanov AA, Doll M, Ruggi A, Scopelliti R, Fadaie-Tirani F, Angew. Chem 2020, 132, 10043–10047;Angew. Chem. Int. Ed 2020, 59, 9957–9961.

[13]. Matsui JK, Lang SB, Heitz DR, Molander GA, ACS Catal. 2017, 7, 2563–2575. [PubMed: 28413692]

[14]. Burkhart JP, Weintraub PM, Gates CA, Resvick RJ, Vaz RJ, Friedrich D, Angelastro MR, Bey P, Peet NP, Bioorg. Med. Chem 2002, 10, 929–934. [PubMed: 11836100]

[15]. [a]Wermuth CG, Aldous D, Raboisson P, Rognan D, The practice of medicinal chemistry, Academic Press, Oxford, 2015, p. 210–212.[b]Chandrakumar NS, Yonan PK, Stapelfeld A, Savage M, Rorbacher E, Contreras PC, Hammond D, J. Med. Chem 1992, 35, 223–233. [PubMed: 1346276]

[16]. [a]Wang J, Roselló MS-, Aceña JL, Pozo CD, Sorochinsky AE, Fustero S, Soloshonok VA, Liu H, Chem. Rev 2014, 114, 2432–2506. [PubMed: 24299176] [b]Meanwell NA, J. Med. Chem 2018, 61, 5822–5880. [PubMed: 29400967]

[17]. [a]Furuya T, Ritter T, Org. Lett 2009, 11, 2860–2863. [PubMed: 19507870] [b]Ye Y, Sanford MS, J. Am. Chem. Soc 2013, 135, 4648–4651. [PubMed: 23485148] [c]Fier PS, Luo J, Hartwig JF, J. Am. Chem. Soc 2013, 135, 2552–2559. [PubMed: 23384209]

[18]. Ye Y, Schimler SD, Hanley PS, Sanford MS, J. Am. Chem. Soc 2013 135, 16292–16295. [PubMed: 24160267]

[19]. Okoromoba OE, Han J, Hammond GB, Xu B, J. Am. Chem. Soc 2014 136, 14381–14384. [PubMed: 25260170]

[20]. [a]Drouin M, Hamel J–D, Paquin J–F, Synthesis 2018, 50, 881–955.[b]Yanai H, Taguchi T, Eur. J. Org. Chem 2011, 30, 5939–5954.[c]McCarthy JR, Matthews DP, Stemerick DM, Huber EW, Bey P, Lippert BJ, Snyder RD, Sunkara PS, J. Am. Chem. Soc 1991, 113, 7439–7440.[d]Burton DJ, Greenlimb PE, J. Org. Chem 1975, 40, 2796–2800.

[21]. Niggemann M, Gao S, Angew. Chem 2018, 130, 17186–17188;Angew. Chem. Int. Ed 2018, 57, 16942–16944.
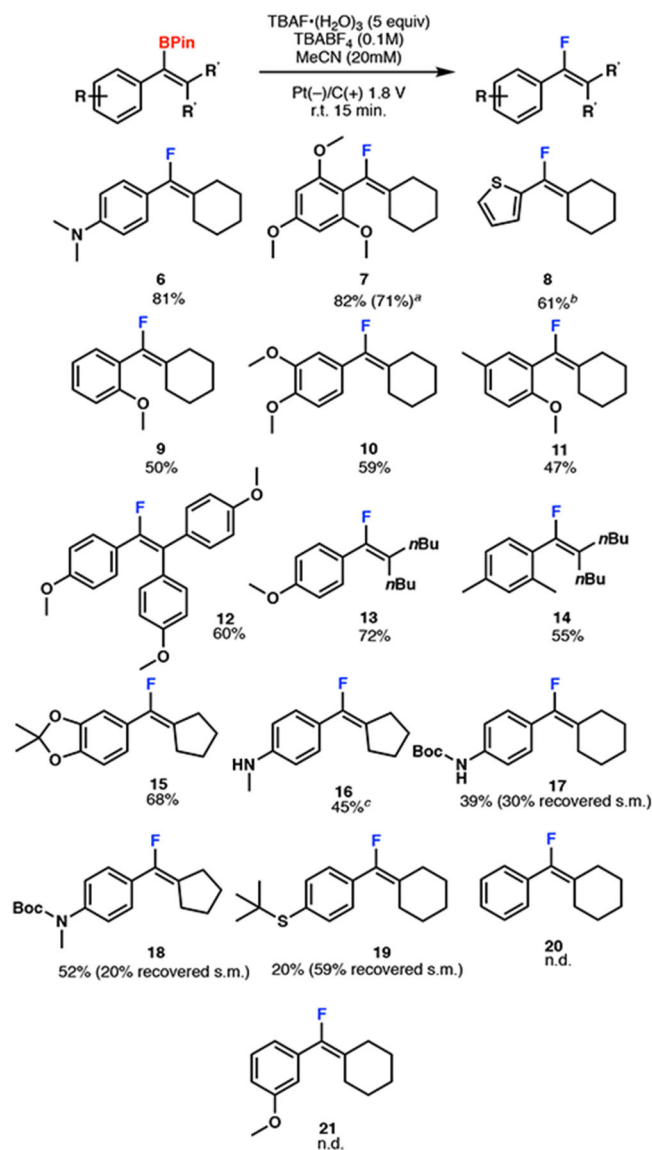
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  Access to alkyl carbocations
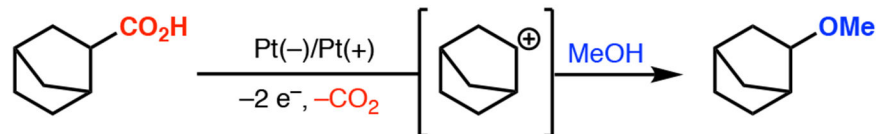
b) *Electrochemical fluorination of vinyl boronates*
 **This research, via putative vinyl carbocations**
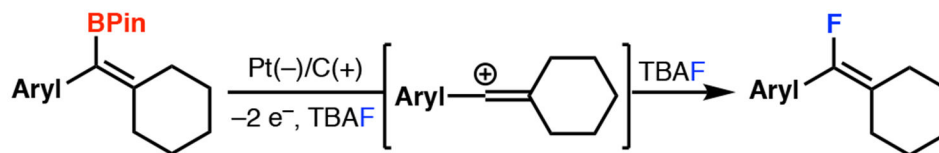
Scheme 1.
Previous work and this study. (a) Hofer-Moest electrochemical oxidation. (b) this research: electrochemical fluorination of alkenyl boronates *via* vinyl carbocations.

Scheme 2.
Scope of alkenyl boronic ester electrochemical fluorination. Isolated yields. [a] 3 equiv of TBAF on 1 mmol scale. [b] Isolated as a 9:1 mixture of fluoride:styrene. [c] +0.8 V *vs* SCE. n.d.=not detected
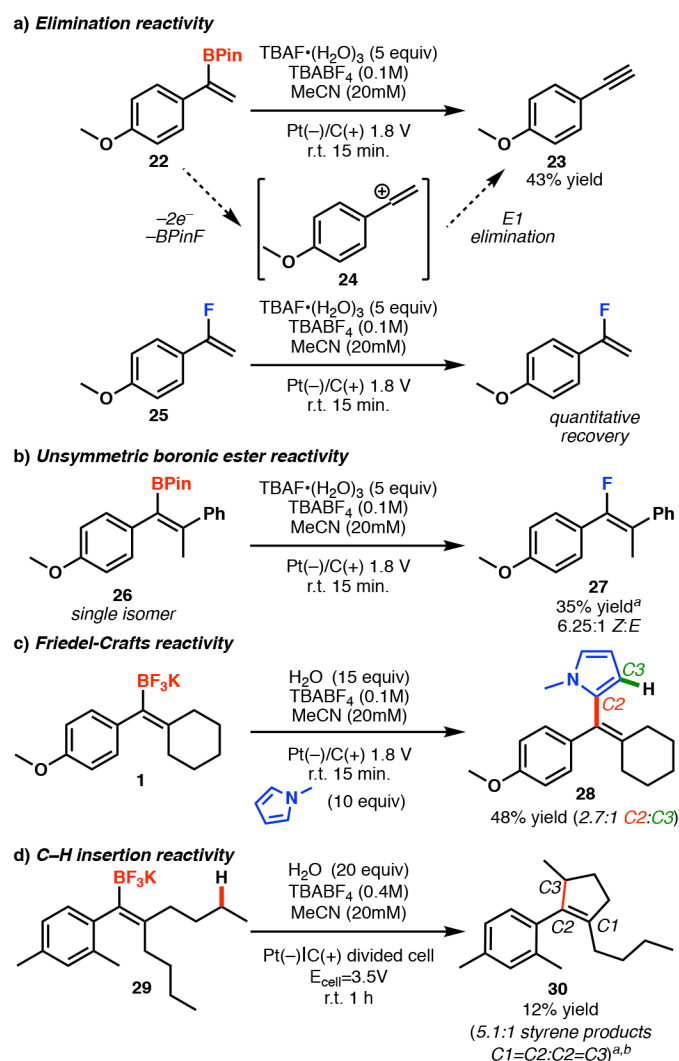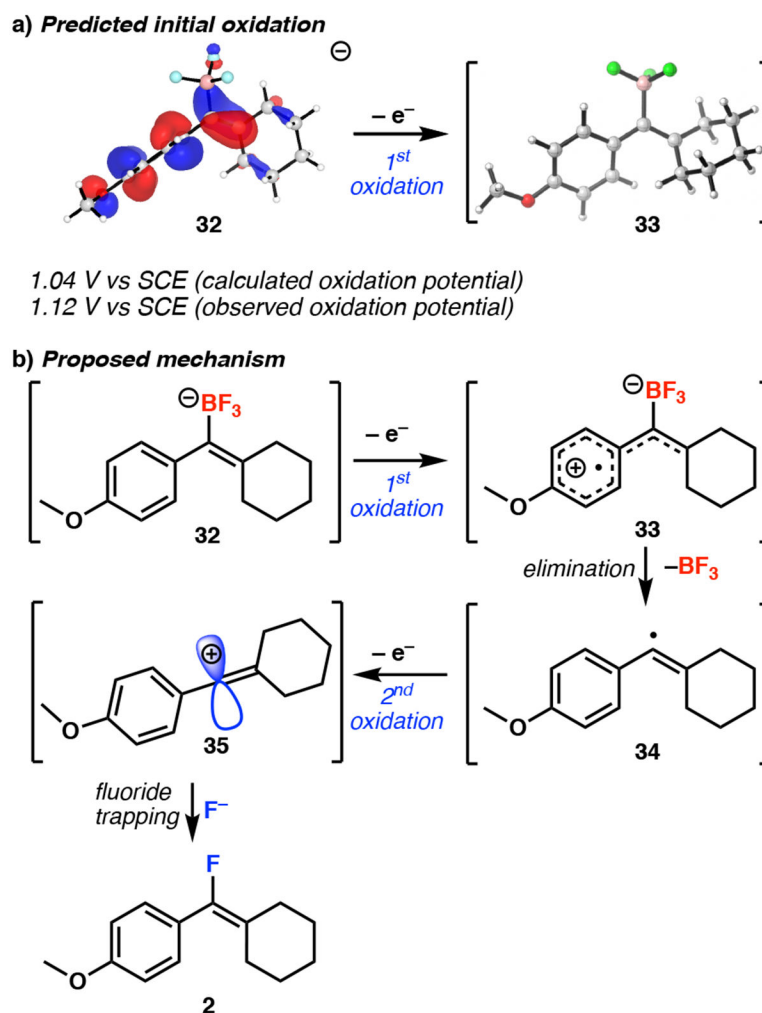
Scheme 3.

Mechanistic experiments to probe for vinyl carbocation reactivity. (a) Elimination reactivity suggesting vinyl carbocation intermediate. (b) Unsymmetric alkenyl boronic ester reactivity. (c) Friedel-Crafts reactivity with N-Me pyrrole. (d) C—H Insertion reactivity. Isolated yields. [a] Yield determined by ^{1}H NMR with an internal standard. [b] Ratio of styrene olefin isomers determined by GC-FID.
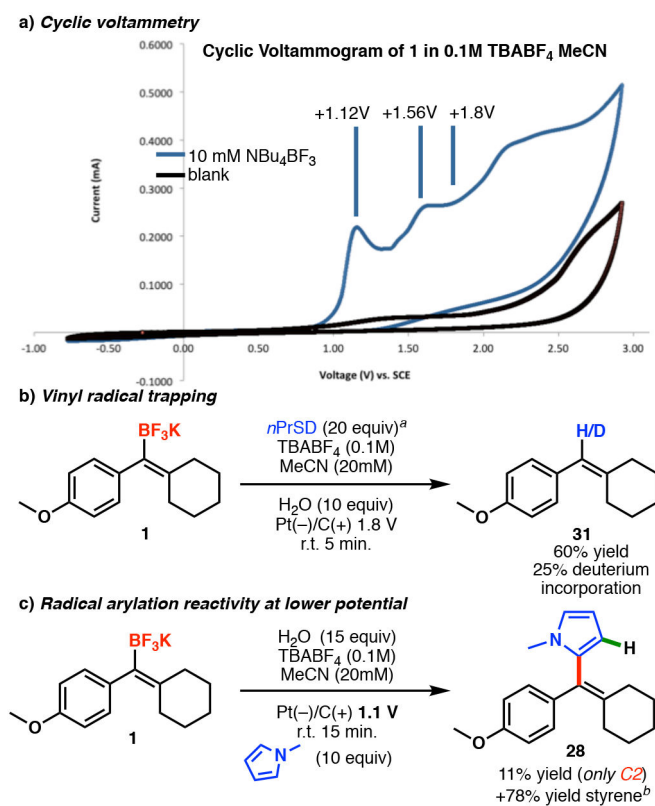
Scheme 4.

Mechanistic experiments to probe for vinyl radical intermediate. (a) Cyclic voltammogram of the tetrabutylammonium salt of **1** in 0.1 M TBABF$_4$ MeCN at 100 mV/s. First and second oxidative waves and +1.8 V of typical reaction highlighted. (b) Styrene products observed in the presence of *n*PrSD. (c) Change of arylation regioselectivity at lower applied potential. [a] Propane thiol prepared at 77% deuteration by isotope exchange with D$_2$O as determined by ^{1}H NMR. [b] Yields determined by ^{1}H NMR with an internal standard. *n*PrSD=deuterium incorporated *n*-propyl thiol.

Scheme 5.
(a) Predicted initial oxidation. (b) Proposed mechanism of boronate fluorination. Calculated HOMO and oxidation potential using (uM06-2X/6-311++G(d,p) cpcm=acetonitrile // uM06-2X/6-31+G(d,p) cpcm=acetonitrile)

Table 1.

Optimization of fluorination from vinyl trifluoroborate 1 and pinacol

boronate **3**. Isolated yields.
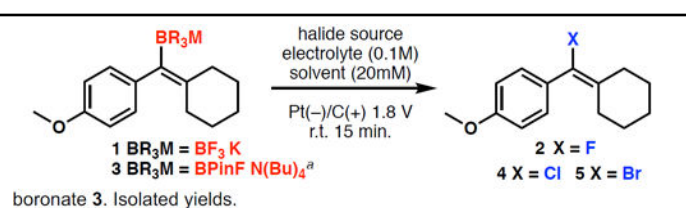
Entry	Starting Material	Solvent	Electrolyte (0.1 M)	Halide Source (equiv)	Yield
1	1	DCM	TBABF$_4$	TBAF•(H$_2$O)$_3$ (5 equiv)	42% [b]
2	1	THF	TBABF$_4$	TBAF•(H$_2$O)$_3$ (5 equiv)	<5% [b]
3	1	DMF	TBABF$_4$	TBAF•(H$_2$O)$_3$ (5 equiv)	n.d.
4	1	MeCN	TBABF$_4$	TBAF•(H$_2$O)$_3$ (5 equiv)	65%
5	3	MeCN	TBABF$_4$	TBAF•(H$_2$O)$_3$ (5 equiv)	70%
6	3	MeCN	TBABF$_4$	TBAF•(H$_2$O)$_3$ (3 equiv)	62%
7	3	MeCN	TBABF$_4$	TBAF•(H$_2$O)$_3$ (2 equiv)	50%
8	3	MeCN	TBABF$_4$	TMAF•(H$_2$O)$_4$ (5 equiv)	49%
9	3	MeCN	TBABF$_4$	TBAF•(tBuOH)$_4$ (5 equiv)	58%
10	3	MeCN	TBABF$_4$	KF+18-Crown-6 (10 equiv)	n.d.
11	3	MeCN	TBABF$_4$	TBAT (5 equiv)	40% [b]
12	3	MeCN	TBAPF$_6$	TBAF•(H$_2$O)$_3$ (5 equiv)	54% [b]
13	3	MeCN	TBABF$_4$	TBAF•(H$_2$O)$_3$ (5 equiv)	19% [b,c]
14	3	MeCN	TBABF$_4$	TBACl (6 equiv)	68%
15	1	MeCN	TBABr	—	57%

[a] Formed *in situ* from the pinacol boronic ester.

[b] ^{19}F NMR yield with fluorobenzene as an internal standard

[c] Added 50 mg mol sieves, MeCN distilled over CaH$_2$ and dried over mol sieves. TBAT=tetrabutyl ammonium difluorotriphenyl silicate, TMAF=tetramethyl ammonium fluoride. n.d.=not detected