OL | Organic Letters

ACS AUTHORCHOICE

pubs.acs.org/OrgLett

Letter

Preparation of α-Perfluoroalkyl Ketones from α,β-Unsaturated Ketones via Formal Hydroperfluoroalkylation

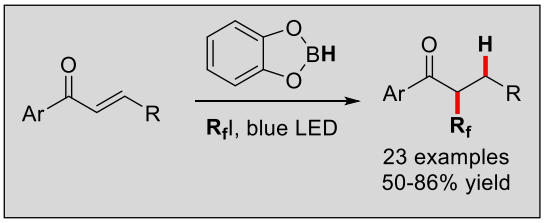
Kalipada Jana, Isao Mizota, and Armido Studer*

Cite This: *Org. Lett.* 2021, 23, 1280–1284

Read Online

ACCESS | Metrics & More | Article Recommendations | Supporting Information

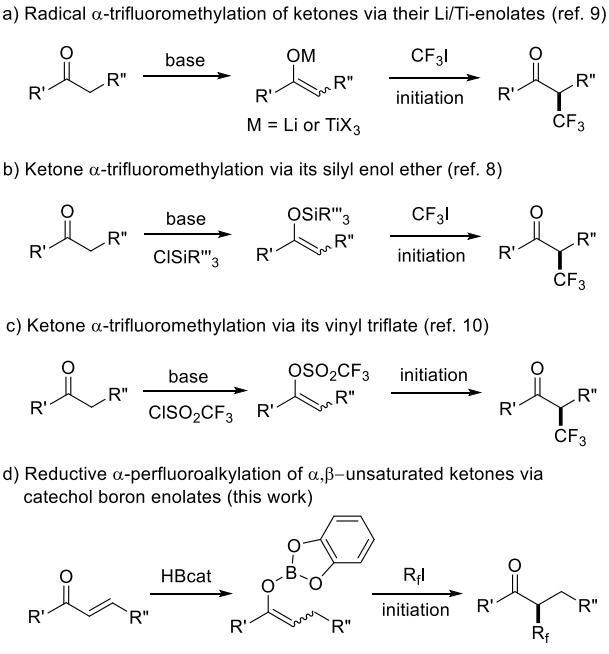
ABSTRACT: Formal hydroperfluoroalkylation of enones is achieved in a two-step process comprising conjugate hydroboration and subsequent radical perfluoroalkylation. The 1,4-hydroboration of the enone is conducted in the absence of any transition metal catalyst with catecholborane in 1,2-dichloroethane, and the generated boron enolate is in situ α-perfluoroalkylated with a perfluoroalkyl iodide upon blue LED irradiation in the presence of an amine additive. Both reactions proceed under very mild conditions at room temperature.



Perfluoroalkyl containing organic compounds have gained great importance in various fields such as polymer chemistry, the agrochemical industry, and the pharmaceutical industry.[1] Various agrochemicals and pharmaceuticals bear at least one fluorine atom.[2] It is well-known that a perfluoroalkyl group, in particular the CF_3-moiety, in a bioactive compound influences the pharmacokinetics.[3] Therefore, the development of synthetic methods for the preparation of perfluoroalkylated compounds has found significant attention in the past, and various strategies have been developed to form a $C(sp^3)-CF_3$ bond using electrophilic,[4] nucleophilic,[5] and radical[6] CF_3-sources.

Among several scaffolds, the synthesis of α-trifluoromethylated ketones has been studied, and accordingly, different approaches for their preparation have been reported. The most obvious path that is ionic enolate alkylation using CF_3I as the electrophile does not provide the targeted α-trifluoromethylated ketones. However, $C(sp^3)-CF_3$ coupling can be achieved upon using α-halo ketones with $CuCF_3$ as the reagent.[7] Moreover, radical chemistry with the reactive trifluoromethyl radical as an intermediate has been found to be highly valuable for the α-trifluoromethylation of ketones.[8−10] Along these lines, Li- and Ti-enolates have been successfully used as radical acceptors for trifluoromethylation (Scheme 1a).[9] In situ generated silyl enol ethers react efficiently with CF_3I in a radical chain reaction and different initiation protocols have been developed to run such cascades (Scheme 1b).[8] Moreover, vinyl triflates, readily prepared upon enolate triflation, act as CF_3-radical acceptors as well as CF_3-radical precursors with SO_2 as the only byproduct of the chain reaction (Scheme 1c).[10] All these methods use ketones as the substrates and all proceed via formation of the corresponding enolates. It is known that ketone enolates can also be generated via conjugate reduction of enones. Subsequent α-trifluoromethylation should provide the targeted α-functionalized ketones in a formal hydrotrifluoromethylation[11] process. Surprisingly, reductive enone α-trifluoromethylation has been rarely studied.[12] Herein, we report a catalyst-free α-perfluoroalkylation of α,β-unsaturated ketones via conjugate hydroboration

Scheme 1. Radical Approaches for the Preparation of α-Trifluoromethylated Ketones

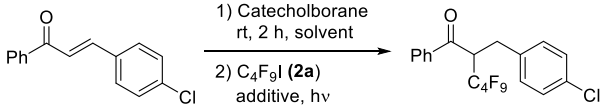


Received: December 26, 2020
Published: February 2, 2021

with catecholborane and subsequent radical perfluoroalkylation of the in situ generated boron enolate (Scheme 1d). In contrast to the generation of silyl enol ethers or enol triflates from ketones where strong bases are generally required, the B-enolate formation via hydroboration of enones occurs in the absence of any base under mild conditions. Moreover, regioselective enolization of dialkyl ketones is difficult, whereas enolization of an enone affords the corresponding enolate as a single regioisomer.

In a collaboration with the Renaud laboratory we developed TEMPO mediated oxidation of catecholboron enolates proceeding via the corresponding enoyl radicals.[13] We further showed that catecholboron enolates are good C-radical acceptors, and based on this reactivity a boron group transfer polymerization process was developed.[14] We therefore envisaged that catecholboron enolates can be utilized as perfluoroalkyl radical acceptors. The studies were commenced using chlorochalcone **1a** as the model substrate in combination with perfluorobutyl iodide (**2a**) as the radical alkylation reagent. In situ generation of the boron enolate through conjugate enone reduction upon treatment of **2a** with catecholborane (HBcat, 1.2 equiv)[15] in THF for 2 h was followed by the addition of **2a** (5 equiv) and subsequent blue LED irradiation for 16 h. Pleasingly, the targeted α-perfluoroalkylated ketone **3a** was obtained in 29% yield (Table 1, entry 1). Increasing the amount of HBcat and **2a** led to a slightly better yield (Table 1, entry 2). A further improvement was achieved upon using DMF as an additive and **3a** was formed in 45% yield (Table 1, entry 3). An even better result was noted with Et_3N as the additive (Table 1, entry 4). A quick solvent screening revealed that yield was improved in dioxane (Table 1, entry 5) and 1,2-dichloroethane provided the best result (84%, Table 1, entry 6). Reducing the excess of the iodide from 5 to 2.5 equiv led to a lower yield (Table 1, entry 7), and light irradiation was indispensable (Table 1, entry 8).

Table 1. Reaction Optimization[a,b]

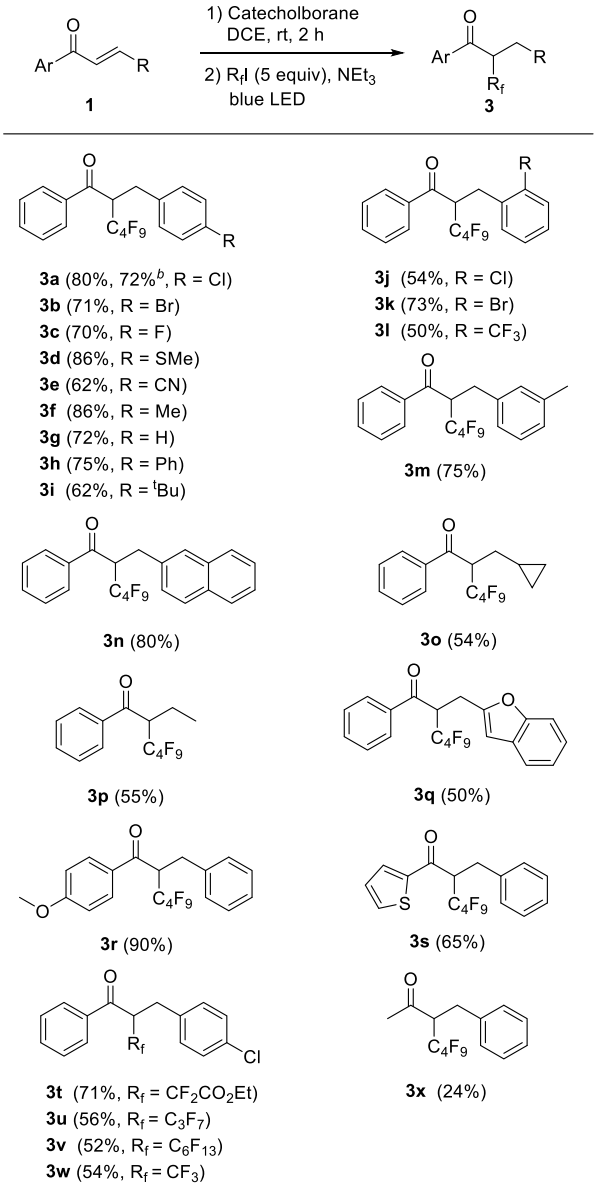


entry	solvent	HBcat (equiv)	additive	**2a** (equiv)	yield (%)
1	THF	1.2	–	5	29
2	THF	2.2	–	10	35
3	THF	1.5	DMF[c]	5	45
4	THF	1.5	Et_3N[d]	5	59[e]
5	dioxane	1.5	Et_3N[d]	5	74
6	**DCE**	**1.5**	**Et_3N**[b]	**5**	**84**
7	DCE	1.5	Et_3N[d]	2.5	60
8	DCE	1.5	Et_3N[d]	5	0[f]

[a]Reaction conditions: **1a** (0.2 mmol, 1 equiv), solvent (1 mL), additive, rt, Ar, 16 h. [b]Yield were determined by NMR using 2,4,6-trimethoxybenzene as internal standard. [c]0.1 mL DMF used. [d]2.5 equiv used. [e]Isolated yield based on **1a**. [f]Without light.

Under the optimized conditions, the substrate scope was investigated, first varying the enone component. The studied enones were easily prepared by standard aldol condensation (see Supporting Information), and reactions were conducted with perfluorobutyl iodide as the C-radical precursor. Chalcones **1a**–**1i** reacted well, and the corresponding products were isolated in good to very good yields (Scheme 2). Electronic effect are weak and good results were obtained for the electron-poor as well as electron-rich systems. Hence, the 4-halo chalcones **1a**–**1c** and the nitrile **1e** gave the hydroperfluoroalkylated ketones **3a**–**3c** and **3e** in 62–80% yields. Similar yields were obtained for the chalcones bearing electron-donating alkyl and the methylthio group as the *para*-substituent (**3d**, 86%; **3f**, 86%; **3i**, 62%), and also the unsubstituted congener **1g** as well as the phenyl derivative **1h** reacted well (**3g**, 72%; **3h**, 75%).

Scheme 2. Hydroperfluoroalkylation of Various Enones Also Varying the Perfluoroalkyl Radical Precursor[a]



[a]Reaction conditions: **1** (0.2 mmol, 1 equiv), DCE (1 mL), HBCat (0.3 mmol, 1.5 equiv), Et_3N (69 μL, 2.5 equiv), rt, Ar, 16 h. [b]Reaction conducted on 1 mmol scale.

The hydroperfluoroalkylated ketones **3a**–**3c** and **3e** in 62–80% yields. Similar yields were obtained for the chalcones bearing electron-donating alkyl and the methylthio group as the *para*-substituent (**3d**, 86%; **3f**, 86%; **3i**, 62%), and also the unsubstituted congener **1g** as well as the phenyl derivative **1h** reacted well (**3g**, 72%; **3h**, 75%).

Substitution at the *ortho*-position of the R-aryl group in the starting chalcone (see **1j**–**1l**) led to slightly lower yields, likely due to steric effects, and **3j**–**3l** were isolated in 50–73% yields. As expected, a *meta*-substituent does not influence reaction outcome to a large extent (**3m**, 75%). The chalcone derived

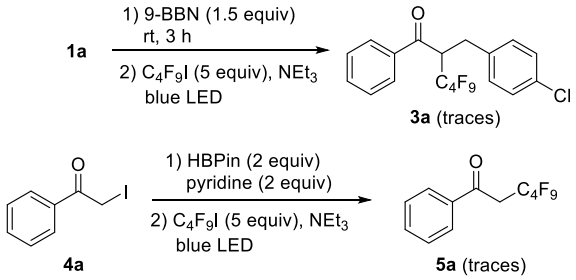
https://dx.doi.org/10.1021/acs.orglett.0c04260
Org. Lett. 2021, 23, 1280–1284

from 2-naphthyl aldehyde exerting weak steric effects reacted efficiently to provide **3n** in 80% yield. We were pleased to find that enones derived from aliphatic aldehydes engaged in the hydroperfluoroalkylation as documented by the successful preparation of the cyclopropyl- (**3o**) and methyl congener (**3p**), albeit slightly lower yields were achieved (54−55%). Moreover, heteroarenes are tolerated as the benzofuryl (**3q**) and thienyl ketone (**3s**) could be prepared by this method. The latter example further shows that also the Ar-group in the enones of type **1** can be varied. Along these lines, the *para*-methoxyphenyl ketone **3r** was obtained in an excellent 90% yield. Unfortunately, cyclic enones are not eligible substrates due to the failure of the initial conjugate hydroboration.[15] Methyl styryl ketone worked, albeit the yield was moderate (**3x**, 24%).

We finally tested whether the perfluorobutyl iodide can be replaced by other perfluoroalkyl radical sources. Pleasingly, reaction of ICF_2CO_2Et with **1a** under the optimized conditions gave the desired ketone **3t** in 71% yield. As expected, the novel cascade can also be conducted with perfluoropropyl iodide (**3u**), perfluorohexyl iodide (**3v**), and importantly also with trifluoromethyl iodide (**3w**).

To check the role of the catecholboron moiety in the radical alkylation, we studied the α-perfluorobutylation of two additional boron enolates. The enolate derived from conjugate reduction of 4-chlorochalcone (**1a**) with 9-borabicyclo[3.3.1]-nonane (9-BBN)[16] was reacted with C_4F_9I under the optimized condition (LED irradiation). However, only traces of the targeted **3a** were identified (Scheme 3). In addition, we

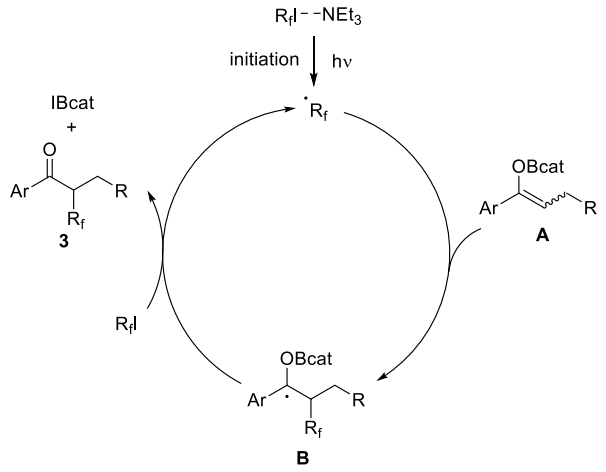
Scheme 3. Control Experiments: The Importance of the Catecholboron Moiety



generated the pinacol boron enolate derived from α-iodoacetophenone (**4a**).[17] Again, radical α-perfluorobutylation was not efficient upon irradiation, and **5a** was formed in traces only. In both cases reduction worked, but the subsequent radical C−R_f-bond formation failed. These two experiments clearly show the importance of the catechol moiety at boron on its radical reactivity. Notably, the unique reactivity of the catechol entity was previously also found for the boron enolate oxidation with TEMPO.[13]

The suggested mechanism for the radical perfluoroalkylation of a catecholboron enolate **A** is depicted in Scheme 4. In the initiation step, the perfluoroalkyl radical is generated by blue LED irradiation of the perfluoroalkyl iodide/amine complex. The electrophilic C-radical then adds to the catecholboron enolate **A** to generate the corresponding borylated ketyl radical **B**. Structure of **A** was confirmed for the enolate derived from **1a** (Ar = Ph, R = 4-ClPh) by NMR spectroscopy (see SI). For this particular substrate, enolate generation occurred selectively and the *Z*-configuration was assigned based on literature precedence.[15a] This highly nucleophilic radical can undergo

Scheme 4. Proposed Mechanism



rapid SET-oxidation by the perfluoroalkyl iodide to give the product ketone **3**, IBcat and the perfluoroalkyl radical, qualifying the overall cascade as an electron catalyzed process.[18] The SET-oxidation of intermediate **B** might be assisted with the Lewis-basic amine coordinating to the B atom of the enolate.[19] Alternatively, radical **B** might engage in an endothermic I atom abstraction reaction from R_fI followed by very fast ionic IBcat fragmentation.

In summary, we have presented formal hydroperfluoroalkylation of various aromatic enones. These transformations proceed via initial conjugate reduction of the α,β-unsaturated ketone with catecholborane and subsequent light initiated radical chain α-perfluoroalkylation of the intermediately formed catecholboron enolate. The radical alkylation works only on catecholboron enolates and analogous pinacolboron- and dialkyl boron enolates do not engage in the radical alkylation. The process works under mild conditions, and a catalyst is not required in both steps of the cascade. Importantly, the two-step procedure can be conducted in one pot, further increasing the practicality of the process. The method introduced further expands boron-based radical chemistry.[20]

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.orglett.0c04260.

Experimental details and characterization data; NMR spectra of new compounds (PDF)

■ AUTHOR INFORMATION

Corresponding Author

Armido Studer − *Organisch-Chemisches Institut, Westfälische Wilhelms-Universität, 48149 Münster, Germany;* orcid.org/0000-0002-1706-513X; Email: studer@uni-muenster.de

Authors

Kalipada Jana − *Organisch-Chemisches Institut, Westfälische Wilhelms-Universität, 48149 Münster, Germany*

Isao Mizota − *Organisch-Chemisches Institut, Westfälische Wilhelms-Universität, 48149 Münster, Germany;* orcid.org/0000-0003-0760-677X

https://dx.doi.org/10.1021/acs.orglett.0c04260
Org. Lett. 2021, 23, 1280−1284

Complete contact information is available at:
https://pubs.acs.org/10.1021/acs.orglett.0c04260

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We thank the European Research Council (Advanced Grant Agreement No. 692640) for supporting this work and the The Daiichi Sankyo Foundation of Life Science program for a Research Fellowship (I.M.).

■ REFERENCES

(1) (a) Mikami, K.; Itoh, Y.; Yamanaka, M. Fluorinated Carbonyl and Olefinic Compounds: Basic Character and Asymmetric Catalytic Reactions. *Chem. Rev.* **2004**, *104*, 1−16. (b) Böhm, H.-J.; Banner, D.; Bendels, S.; Kansy, M.; Kuhn, B.; Müller, K.; Obst-Sander, U.; Stahl, M. Fluorine in Medicinal Chemistry. *ChemBioChem* **2004**, *5*, 637−643. (c) Ma, J.-A.; Cahard, D. Asymmetric Fluorination, Trifluoromethylation, and Perfluoroalkylation Reactions. *Chem. Rev.* **2004**, *104*, 6119−6146. (d) O'Hagan, D. Understanding organofluorine chemistry. An introduction to the C−F bond. *Chem. Soc. Rev.* **2008**, *37*, 308−319.

(2) (a) Hagmann, W. K. The Many Roles for Fluorine in Medicinal Chemistry. *J. Med. Chem.* **2008**, *51*, 4359−4369. (b) Meanwell, N. A. Synopsis of Some Recent Tactical Application of Bioisosteres in Drug Design. *J. Med. Chem.* **2011**, *54*, 2529−2591. (c) Ilardi, E. A.; Vitaku, E.; Njardarson, J. T. Data-Mining for Sulfur and Fluorine: An Evaluation of Pharmaceuticals To Reveal Opportunities for Drug Design and Discovery. *J. Med. Chem.* **2014**, *57*, 2832−2842.

(3) Müller, K.; Faeh, C.; Diederich, F. Fluorine in Pharmaceuticals: Looking Beyond Intuition. *Science* **2007**, *317*, 1881−1886.

(4) For electrophilic trifluoromethylation, see: (a) Umemoto, T.; Ishihara, S. Power-variable electrophilic trifluoromethylating agents. S-, Se-, and Te-(trifluoromethyl)dibenzothio-, -seleno-, and -tellurophenium salt system. *J. Am. Chem. Soc.* **1993**, *115*, 2156−2164. (b) Kieltsch, I.; Eisenberger, P.; Togni, A. Mild Electrophilic Trifluoromethylation of Carbon- and Sulfur-Centered Nucleophiles by a Hypervalent Iodine(III)−CF_3 Reagent. *Angew. Chem., Int. Ed.* **2007**, *46*, 754−757. (c) Allen, A. E.; MacMillan, D. W. C. The Productive Merger of Iodonium Salts and Organocatalysis: A Nonphotolytic Approach to the Enantioselective α-Trifluoromethylation of Aldehydes. *J. Am. Chem. Soc.* **2010**, *132*, 4986−4987. (d) Charpentier, J.; Früh, N.; Togni, A. Electrophilic Trifluoromethylation by Use of Hypervalent Iodine Reagents. *Chem. Rev.* **2015**, *115*, 650−682. (e) Prieto, A.; Baudoin, O.; Bouyssi, D.; Monteiro, N. Electrophilic trifluoromethylation of carbonyl compounds and their nitrogen derivatives under copper catalysis. *Chem. Commun.* **2016**, *52*, 869−881. (f) Gelat, F.; Patra, A.; Pannecoucke, X.; Biju, A. T.; Poisson, T.; Besset, T. N-Heterocyclic Carbene-Catalyzed Synthesis of α-Trifluoromethyl Esters. *Org. Lett.* **2018**, *20*, 3897−3901. (g) Yang, W.; Ma, D.; Zhou, Y.; Dong, X.; Lin, Z.; Sun, J. NHC-Catalyzed Electrophilic Trifluoromethylation: Efficient Synthesis of γ-Trifluoromethyl α,β-Unsaturated Esters. *Angew. Chem., Int. Ed.* **2018**, *57*, 12097−12101.

(5) For nucleophilic trifluoromethylation, see: (a) Prakash, G. K. S.; Yudin, A. K. Perfluoroalkylation with Organosilicon Reagents. *Chem. Rev.* **1997**, *97*, 757−786. (b) Prakash, G. K. S.; Wang, F.; Zhang, Z.; Haiges, R.; Rahm, M.; Christe, K. O.; Mathew, T.; Olah, G. A. Long-Lived Trifluoromethanide Anion: A Key Intermediate in Nucleophilic Trifluoromethylations. *Angew. Chem., Int. Ed.* **2014**, *53*, 11575−11578.

(6) Selected recent reports on radical trifluoromethylation, see: (a) Studer, A. A "Renaissance" in Radical Trifluoromethylation. *Angew. Chem., Int. Ed.* **2012**, *51*, 8950−8958. (b) Li, Y.; Studer, A. Transition-Metal-Free Trifluoromethylaminoxylation of Alkenes. *Angew. Chem., Int. Ed.* **2012**, *51*, 8221−8224. (c) Zhou, S.; Song, T.; Chen, H.; Liu, Z.; Shen, H.; Li, C. Catalytic Radical Trifluoromethylalkynylation of Unactivated Alkenes. *Org. Lett.* **2017**, *19*, 698−701. (d) Le, C.; Chen, T. Q.; Liang, T.; Zhang, P.; MacMillan, D. W. C. A radical approach to the copper oxidative addition problem: Trifluoromethylation of bromoarenes. *Science* **2018**, *360*, 1010−1014. (e) Ouyang, Y.; Xu, X.-H.; Qing, F.-L. Trifluoromethanesulfonic Anhydride as a Low-Cost and Versatile Trifluoromethylation Reagent. *Angew. Chem., Int. Ed.* **2018**, *57*, 6926−6929. (f) Chang, B.; Su, Y.; Huang, D.; Wang, K.-H.; Zhang, W.; Shi, Y.; Zhang, X.; Hu, Y. Synthesis of Trifluoroethyl Pyrazolines via Trichloroisocyanuric Acid Promoted Cascade Cyclization/Trifluoromethylation of β,γ-Unsaturated Hydrazones. *J. Org. Chem.* **2018**, *83*, 4365−4374. (g) Ouyang, Y.; Xu, X.-H.; Qing, F.-L. *Angew. Chem., Int. Ed.* **2018**, *57*, 6926−6929. (h) Jana, K.; Bhunia, A.; Studer, A. Radical 1,3-Difunctionalization of Allylboronic Esters with Concomitant 1,2-Boron Shift. *Chem.* **2020**, *6*, 512−522.

(7) Novák, P.; Lishchynskyi, A.; Grushin, V. V. Trifluoromethylation of α-Haloketones. *J. Am. Chem. Soc.* **2012**, *134*, 16167−16170.

(8) For α-trifluoromethylation of ketones via silyl enol ethers, see (a) Miura, K.; Taniguchi, M.; Nozaki, K.; Oshima, K.; Utimoto, K. Triethylborane induced perfluoroalkylation of silyl enol ethers or germyl enol ethers with perfluoroalkyl iodides. *Tetrahedron Lett.* **1990**, *31*, 6391−6394. (b) Mikami, K.; Tomita, Y.; Ichikawa, Y.; Amikura, K.; Itoh, Y. Radical Trifluoromethylation of Ketone Silyl Enol Ethers by Activation with Dialkylzinc. *Org. Lett.* **2006**, *8*, 4671−4673. (c) Sato, K.; Yuki, T.; Yamaguchi, R.; Hamano, T.; Tarui, A.; Omote, M.; Kumadaki, I.; Ando, A. Mechanistic Studies on α-Trifluoromethylation of Ketones via Silyl Enol Ethers and Its Application to Other Carbonyl Compounds. *J. Org. Chem.* **2009**, *74*, 3815−3819. (d) Pham, P. V.; Nagib, D. A.; MacMillan, D. W. C. Photoredox Catalysis: A Mild, Operationally Simple Approach to the Synthesis of α-Trifluoromethyl Carbonyl Compounds. *Angew. Chem., Int. Ed.* **2011**, *50*, 6119−6122.

(9) For α-trifluoromethylation of ketones via their Ti- and Li-enolates, see: (a) Itoh, Y.; Mikami, K. Radical Trifluoromethylation of Titanium Ate Enolate. *Org. Lett.* **2005**, *7*, 649−651. (b) Itoh, Y.; Mikami, K. Facile Radical Trifluoromethylation of Lithium Enolates. *Org. Lett.* **2005**, *7*, 4883−4885. (c) Itoh, Y.; Houk, K. N.; Mikami, K. Experimental and Theoretical Studies on Radical Trifluoromethylation of Titanium Ate and Lithium Enolates. *J. Org. Chem.* **2006**, *71*, 8918−8925.

(10) (a) Su, X.; Huang, H.; Yuan, Y.; Li, Y. Radical Desulfur-Fragmentation and Reconstruction of Enol Triflates: Facile Access to α-Trifluoromethyl Ketones. *Angew. Chem., Int. Ed.* **2017**, *56*, 1338−1341. (b) Kawamoto, T.; Sasaki, R.; Kamimura, A. Synthesis of α-Trifluoromethylated Ketones from Vinyl Triflates in the Absence of External Trifluoromethyl Sources. *Angew. Chem., Int. Ed.* **2017**, *56*, 1342−1345.

(11) Clausen, F.; Kischkewitz, M.; Bergander, K.; Studer, A. Catalytic Protodeboronation of Pinacol Boronic Esters: Formal Anti-Markovnikov Hydromethylation of Alkenes. *Chem. Sci.* **2019**, *10*, 6210−6214.

(12) Sato, K.; Omote, M.; Ando, A.; Kumadaki, I. Rhodium-Catalyzed Novel Trifluoromethylation at the α-Position of α,β-Unsaturated Ketones. *Org. Lett.* **2004**, *6*, 4359−4361.

(13) (a) Pouliot, M.; Renaud, P.; Schenk, K.; Studer, A.; Vogler, T. Oxidation of Catecholboron Enolates with TEMPO. *Angew. Chem., Int. Ed.* **2009**, *48*, 6037−6040. (b) Li, Y.; Pouliot, M.; Vogler, T.; Renaud, P.; Studer, A. α-Aminoxylation of Ketones and β-Chloro-α-aminoxylation of Enones with TEMPO and Chlorocatecholborane. *Org. Lett.* **2012**, *14*, 4474−4477.

(14) Uehara, K.; Wagner, C. B.; Vogler, T.; Luftmann, H.; Studer, A. Poly(vinyl ketone)s by Controlled Boron Group Transfer Polymerization (BGTP). *Angew. Chem., Int. Ed.* **2010**, *49*, 3073−3076.

(15) (a) Evans, D. A.; Fu, G. C. Conjugate reduction of α,β-unsaturated carbonyl compounds by catecholborane. *J. Org. Chem.* **1990**, *55*, 5678−5680. (b) Matsumoto, Y.; Hayashi, T. Selective 1,4-Hydroboration of Phenyl 1-Alkenyl Ketones with 9-Borabicyclo

[3.3.1] nonane and Catecholborane Forming Boron (*Z*)-Enolates. *Synlett* **1991**, *1991*, 349−350.
(16) Kiyokawa, K.; Nagata, T.; Minakata, S. Electrophilic Cyanation of Boron Enolates: Efficient Access to Various *β*-Ketonitrile Derivatives. *Angew. Chem., Int. Ed.* **2016**, *55*, 10458−10462.
(17) Mukaiyama, T.; Takuwa, T.; Yamane, K.; Imachi, S. Stereoselective Crossed Aldol Reaction via Boron Enolates Generated from *α*-Iodo Ketones and 9-Borabicyclo[3.3.1]nonane. *Bull. Chem. Soc. Jpn.* **2003**, *76*, 813−823.
(18) (a) Studer, A.; Curran, D. P. The electron is a catalyst. *Nat. Chem.* **2014**, *6*, 765−773. (b) Studer, A.; Curran, D. P. Catalysis of Radical Reactions: A Radical Chemistry Perspective. *Angew. Chem., Int. Ed.* **2016**, *55*, 58−102.
(19) Cheng, Y.; Mück-Lichtenfeld, C.; Studer, A. Transition Metal-Free 1,2-Carboboration of Unactivated Alkenes. *J. Am. Chem. Soc.* **2018**, *140*, 6221−6225.
(20) (a) Ollivier, C.; Renaud, P. Organoboranes as a Source of Radicals. *Chem. Rev.* **2001**, *101*, 3415−3434. (b) Friese, F. W.; Studer, A. New avenues for C−B bond formation via radical intermediates. *Chem. Sci.* **2019**, *10*, 8503−8518. (c) Kumar, N.; Reddy, R. R.; Eghbarieh, N.; Masarwa, A. *α*-Borylalkyl radicals: their distinctive reactivity in modern organic synthesis. *Chem. Commun.* **2020**, *56*, 13−25. (d) Kischkewitz, M.; Friese, F. W.; Studer, A. Radical-induced 1,2-Migrations of Boron Ate Complexes. *Adv. Synth. Catal.* **2020**, *362*, 2077−2087.

https://dx.doi.org/10.1021/acs.orglett.0c04260
Org. Lett. 2021, 23, 1280−1284