

Fluorination

AgF-Mediated Fluorinative Cross-Coupling of Two Olefins: Facile Access to α -CF₃ Alkenes and β -CF₃ Ketones**

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Abstract: A AgF-mediated fluorination with a concomitant cross-coupling between a *gem*-difluoroolefin and a non-fluorinated olefin is reported. This highly efficient method provides facile access to both α -CF₃ alkenes and β -CF₃ ketones, which otherwise remain challenging to be directly prepared. The application of this method is further demonstrated by the synthesis of bioactive isoxazoline derivatives. This approach represents a conceptually novel route to trifluoromethylated compounds that combines the *in situ* generation of the CF₃ moiety and a C–H functionalization in a single reaction system.

The trifluoromethyl (CF₃) group often significantly alters the acidity, lipophilicity, metabolic stability, and conformation of a molecule; molecules with a trifluoromethyl group are therefore valuable compounds in pharmaceutical chemistry, agrochemistry, and material science.^[1] Accordingly, the incorporation of CF₃ group(s) into a target molecule is highly desirable owing to the nearly complete absence of fluorine in naturally occurring organic molecules.^[2] To date, research efforts have mainly focused on the direct trifluoromethylation (especially transition-metal-mediated coupling reactions) of prefunctionalized compounds with a set of nucleophilic, electrophilic, or radical trifluoromethyl sources.^[3] An alternative route to trifluoromethylated compounds entails the use of CF₃-containing building blocks without the involvement of direct C–CF₃ bond formation.^[4] In both cases, the CF₃ groups are already present in the starting materials, and chemists then have to tailor these substrates into the desired compounds. However, there have been rare examples of combining the *in situ* construction of the CF₃ motif and the functionalization of target molecules by C–C bond formation in a single reaction system. One pioneering work that matches this criterion was reported by Chen and co-workers, who have achieved the copper-mediated trifluoromethylation of aryl halides with methyl fluorosulfonyldifluoroacetate (FSO₂CF₂CO₂Me).^[5a–c] In their system, the reaction of the

difluorocarbene with the fluoride anion and CuI to form the “CuCF₃” intermediate and the copper-mediated coupling with electrophiles are compatible. Compared to direct trifluoromethylation, this *in situ* strategy has advantages for the preparation of [¹⁸F]CF₃ compounds for PET imaging because of its simple manipulation procedure and excellent efficacy.^[5d] Nevertheless, novel methods for the synthesis of trifluoromethylated compounds that are based on similar concepts have rarely been reported since. One major challenge is the *in situ* generation of the CF₃ motif as nearly all CF₃ moieties currently used are originally obtained by fluorination with harsh reaction conditions.^[6]

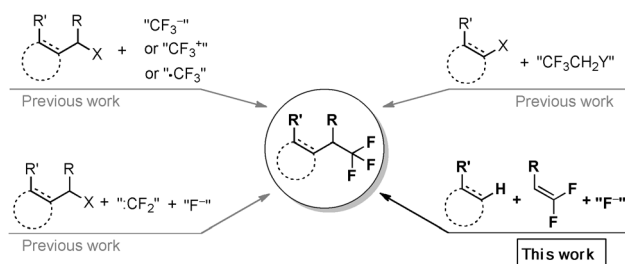
We envisioned that the *gem*-difluorovinyl group would be an attractive alternative CF₃ precursor. The difluoromethylene carbon atom is electrophilic because of the inductive effect of the fluorine atoms and electron repulsion between the double bond and the fluorine atoms, which facilitates the regioselective nucleophilic fluorination of the *gem*-difluoromethylene carbon atom to afford a CF₃ group.^[1a,7] In the past, this α -CF₃ carbanion formed from direct fluoride addition was found to be unstable and would be spontaneously quenched by proton abstraction, making its further functionalization difficult.^[7] We have recently found that β , β -difluorostyrene derivatives reacted with AgF to give the fluorinated homo-coupling products.^[8] Preliminary mechanistic studies implied that an α -CF₃-benzylsilver intermediate, rather than the α -CF₃ carbanion, might be generated although its direct observation failed. Inspired by this result, we settled to explore the concomitant fluorination and intermolecular cross-coupling of a *gem*-difluoroolefin and another reactant as an alternative route to construct more sophisticated CF₃-containing compounds. In this regard, alkenes could be an appealing choice owing to their ready availability and versatile synthetic utility.^[9,10] Herein, we disclose our results on using the *gem*-difluorovinyl group as a CF₃ precursor, which is fluorinated to give an α -trifluoromethylated intermediate; subsequent intermolecular alkenyl C–H functionalization affords α -CF₃ alkenes and β -CF₃ ketones (Scheme 1).

At the onset, 2-(2,2-difluorovinyl)naphthalene (**1a**) was chosen as a model substrate to study its reaction with 1,1-diphenylethylene (**2a**). When the reaction was conducted in pyridine (2.0 mL) at 80 °C for six hours [**1a** (0.5 mmol), **2a** (3.0 equiv), AgF (3.0 equiv)], the fluorination and homo-coupling process of **1a** was so rapid that no cross-coupling products were detected. The solvents were then carefully screened to circumvent the undesired homo-coupling. Fortunately, α -CF₃ alkene **3aa** was formed in 41 % (as determined by ¹⁹F NMR spectroscopy), while 49 % of **1a** did not react, when using 1-methyl-2-pyrrolidinone (NMP) as the solvent under similar reaction conditions. Further screening

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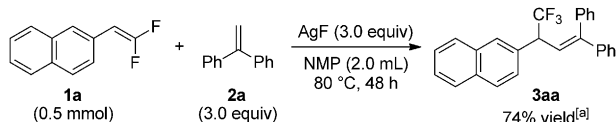
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Scheme 1. Combining the formation of a CF₃ moiety and a C–H functionalization process into a single reaction system.

of the additives, the ratio of the reactions, and the reaction time resulted in the optimized reaction conditions: **1a** (0.5 mmol), **2a** (3.0 equiv), and AgF (3.0 equiv) were heated at 80 °C in NMP for 48 hours under N₂ atmosphere. Thus product **3aa** was obtained in 74 % yield (82 % ¹⁹F NMR yield) while reagent **1a** was fully consumed (Scheme 2).

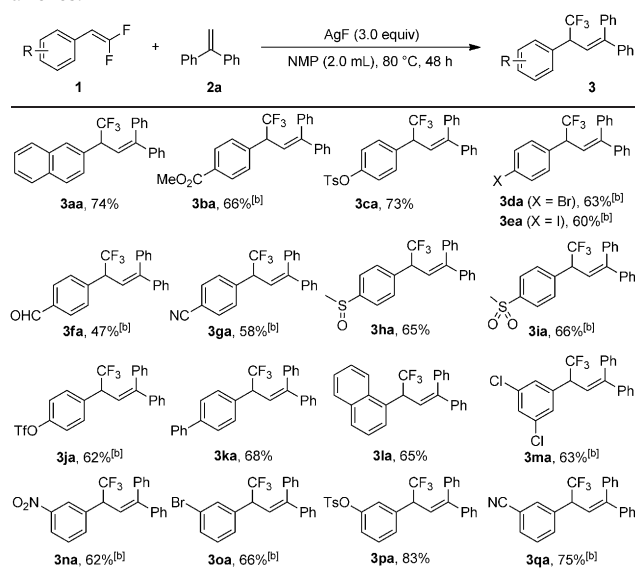


Scheme 2. Optimized reaction conditions for the preparation of α-CF₃ alkenes. [a] Yield determined by ¹⁹F NMR spectroscopy: 82%.

As we have recently disclosed an efficient synthetic access to *gem*-difluoroolefins,^[11] a series of β,β-difluorostyrene derivatives were subjected to the optimized reaction conditions to undergo the cascade reaction. As shown in Table 1, this method is compatible with a wide range of functional groups, including ester, aldehyde, cyano, sulfoxide, sulfone, and even nitro moieties. Moreover, functional groups that are commonly employed in conventional cross-coupling reactions, such as OTf (**3ja**), OTs (**3ca**, **3pa**), and halogen moieties (Cl, Br, I; **3da**, **3ea**, **3ma**, **3oa**), were also tolerated; the corresponding products should thus be easily modifiable by further transformations.^[12] Notably, substrates with electron-withdrawing groups on the aromatic rings were generally more reactive towards AgF, and therefore, the reaction reached completion within eight hours. Meanwhile, using an additional 0.5 equivalents of AgBF₄ was beneficial to suppress the hydrofluorination of electron-deficient *gem*-difluoroolefins (**1b**, **1d–1g**, **1i**, **1j**, **1m–1o**, **1q**). Naphthalene derivative **1l** was also smoothly converted into product **3la** in 65 % yield, indicating the little impact of steric hindrance on the reactivity. It should be mentioned that the fluorination/homo-coupling process of the *gem*-difluoroolefins was minimized to < 3 % in all cases.

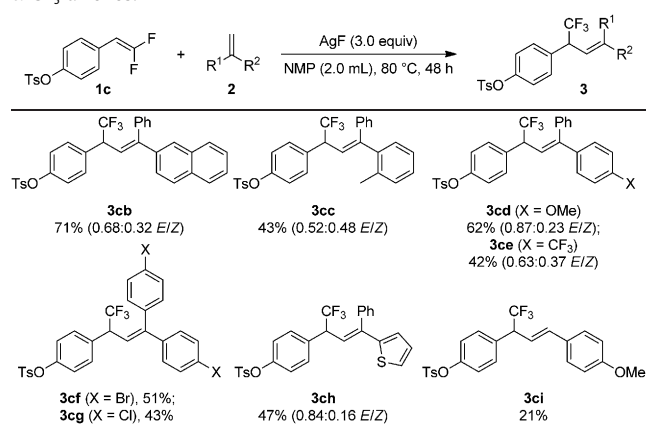
As most of the β,β-difluorostyrene derivatives gave satisfactory results, we also varied the non-fluorinated reaction partners **2** (Table 2). Generally, diaryl ethylenes reacted well with *para*-tosyl β,β-difluorostyrene **1c**, giving the corresponding products in moderate to good yields. Both the steric and electronic properties of the aryl substituents had an

Table 1: Variation of the *gem*-difluoroolefin for the preparation of α-CF₃ alkenes.^[a]



[a] Reaction conditions (unless otherwise specified): **1** (0.5 mmol), **2a** (1.5 mmol), AgF (1.5 mmol), NMP (2.0 mL), 80 °C, 48 h. [b] Reaction conditions B: **1** (0.5 mmol), **2a** (1.5 mmol), AgF (1.5 mmol), AgBF₄ (0.25 mmol), NMP (2.0 mL), 80 °C, 8 h. Tf = trifluoromethanesulfonyl, Ts = *para*-toluenesulfonyl.

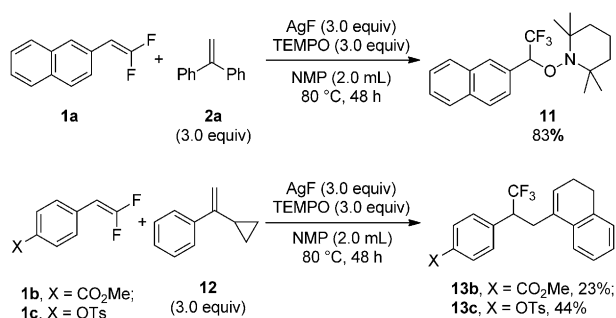
Table 2: Variation of the non-fluorinated alkene for the preparation of α-CF₃ alkenes.^[a]



[a] Reaction conditions: **1c** (0.5 mmol), **2** (1.5 mmol), AgF (1.5 mmol), NMP (2.0 mL), 80 °C, 48 h. The absolute configurations were not determined.

impact on the outcome of the transformations. For instance, substrate **2c**, bearing a proximal methyl group, provided **3cc** as the *Z/E* mixture in relatively low yield. Compared to **2e**, which features an electron-deficient *p*-CF₃ group, **2d**, with an electron-rich *p*-OMe group, was more reactive and gave the corresponding product in higher yield. A substrate with a heteroaryl moiety (**2h**) and α-methylstyrene could also be converted, albeit less effectively. Monosubstituted alkene **2i** also gave a low yield probably because of its poor reactivity.

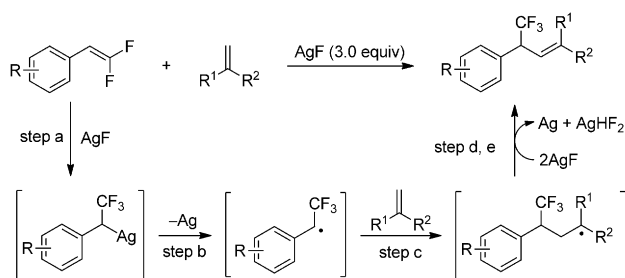
Owing to their synthetic diversity and feasibility, carbonyl-based synthons with a CF₃ substituent have emerged as important intermediates in chemical synthesis.^[13d] In recent



Scheme 5. Mechanistic studies.

was completely inhibited, and the radical trapping adduct **11** was obtained in 83% yield. Furthermore, when (1-cyclopropylvinyl)benzene was subjected to the standard reaction conditions with **1b** and **1c**, the homoallylic trifluoromethylated alkenes **13b** and **13c**, respectively, were isolated as the major products. They were likely the result of the ring opening of the cyclopropane motif followed by intramolecular addition of the carbon radical to the phenyl ring.^[19]

On the basis of these findings and our previous results,^[8] one plausible mechanistic pathway is proposed in Scheme 6. The synergetic addition of AgF to the *gem*-difluoroolefin



Scheme 6. Proposed reaction mechanism.

affords an α -CF₃-benzylsilver intermediate, which undergoes rapid C–Ag^I bond homolysis in situ to afford the α -CF₃-substituted benzyl radical and silver powder; the non-fluorinated alkene then reacts with the α -CF₃ benzyl radical to form a new carbon-centered radical. The resulting carbon radical is oxidized to a carbocation with AgF, followed by rapid deprotonation to give the α -CF₃ alkene, thus completing a net fluorination/intermolecular alkenyl C–H functionalization reaction. It should be noted that AgF is essential and plays at least four different roles in the reaction: It acts 1) as a fluorination reagent that transforms the *gem*-difluorovinyl group into a trifluoromethyl group in step a; 2) as a radical source during C–Ag^I bond homolysis in step b; 3) as an oxidant to convert the carbon radical into a carbocation in step d; and 4) as a base to regenerate the double bond by removing the proton in step e.^[8,20]

In summary, we have developed an efficient *gem*-difluoroolefin fluorination/intermolecular alkenyl C–H functionalization cascade reaction. This method provides facile access to α -CF₃ alkenes as well as to β -CF₃ ketones, which are

otherwise difficult to prepare in a one-pot process. This reaction represents a conceptually novel route for the synthesis of trifluoromethylated compounds that combines the in situ formation of a trifluoromethyl moiety from a *gem*-difluorovinyl group and silver-mediated alkenyl C–H functionalization. Compared with the direct trifluoromethylation or alkylation using CF₃-containing reagents, the current strategy may find potential applications in specific areas, for example, for the preparation of ¹⁸F-labelled CF₃ compounds. Further explorations on the basis of this strategy are underway in our laboratory.

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- [1] a) K. Uneyama, *Organofluorine Chemistry*, Blackwell, Oxford, **2006**; b) P. Kirsch, *Modern Fluoroorganic Chemistry: Synthesis, Reactivity, Applications*, 2nd ed., Wiley-VCH, Weinheim, **2013**; c) J.-P. Bégue, D. Bonnet-Delpon, *Bioorganic and medicinal chemistry of fluorine*, John Wiley & Sons, **2008**; d) A. Sutherland, C. L. Willis, *Nat. Prod. Rep.* **2000**, *17*, 621–631; e) S. Purser, P. R. Moore, S. Swallow, V. Gouverneur, *Chem. Soc. Rev.* **2008**, *37*, 320–330; f) R. Smits, C. D. Cadicamo, K. Burger, B. Koksche, *Chem. Soc. Rev.* **2008**, *37*, 1727–1739; g) M. G. Dhara, S. Banerjee, *Prog. Polym. Sci.* **2010**, *35*, 1022–1077.
- [2] a) The most abundant natural sources of fluorine are the minerals fluorite (CaF₂) and cryolite (Na₃AlF₆); b) D. O'Hagan, D. B. Harper, *J. Fluorine Chem.* **1999**, *100*, 127–133.
- [3] a) J. Charpentier, N. Früh, A. Togni, *Chem. Rev.* **2014**, DOI: 10.1021/cr500223h; b) L. Chu, F.-L. Qing, *Acc. Chem. Res.* **2014**, *47*, 1513–1522; c) H. Egami, M. Sodeoka, *Angew. Chem. Int. Ed.* **2014**, *53*, 8294–8308; *Angew. Chem.* **2014**, *126*, 8434–8449; d) A. Studer, *Angew. Chem. Int. Ed.* **2012**, *51*, 8950–8958; *Angew. Chem.* **2012**, *124*, 9082–9090; e) O. A. Tomashenko, V. V. Grushin, *Chem. Rev.* **2011**, *111*, 4475–4521; f) B. R. Langlois, T. Billard, *Synthesis* **2003**, 185–194; g) G. K. S. Prakash, A. K. Yudin, *Chem. Rev.* **1997**, *97*, 757–786.
- [4] a) J. Nie, H.-C. Guo, D. Cahard, J.-A. Ma, *Chem. Rev.* **2010**, *110*, 455–529; b) K. Uneyama, T. Katagiri, H. Amii, *Acc. Chem. Res.* **2008**, *41*, 817–829; c) J.-P. Bégue, D. Bonnet-Delpon, B. Crousse, J. Legros, *Chem. Soc. Rev.* **2005**, *34*, 562–572; d) Y. Zhao, J. Hu, *Angew. Chem. Int. Ed.* **2012**, *51*, 1033–1036; *Angew. Chem.* **2012**, *124*, 1057–1060.
- [5] a) Q.-Y. Chen, S.-W. Wu, *J. Chem. Soc. Chem. Commun.* **1989**, 705–706; b) Q.-Y. Chen, G.-Y. Yang, S.-W. Wu, *J. Fluorine Chem.* **1991**, *55*, 291–298; c) D.-B. Su, J.-X. Duan, Q.-Y. Chen, *Tetrahedron Lett.* **1991**, *32*, 7689–7690; d) M. Huiban, M. Tredwell, S. Mizuta, Z. Wan, X. Zhang, T. L. Collier, V. Gouverneur, *J. Passchier, Nat. Chem.* **2013**, *5*, 941–944.
- [6] a) T. Umamoto, R. P. Singh, Y. Xu, N. Saito, *J. Am. Chem. Soc.* **2010**, *132*, 18199–18205; b) A. Piou, S. Celerier, S. Brunet, *J. Fluorine Chem.* **2010**, *131*, 1241–1246, and references therein.
- [7] a) P. J. Riss, F. I. Aigbirhio, *Chem. Commun.* **2011**, *47*, 11873–11875; b) L. Zhu, Y. Li, Y. Zhao, J. Hu, *Tetrahedron Lett.* **2010**, *51*, 6150–6152.
- [8] B. Gao, Y. Zhao, C. Ni, J. Hu, *Org. Lett.* **2014**, *16*, 102–105.
- [9] a) T. Peter, *Alkenes and aromatics*, RSC, Cambridge, **2002**; b) P. Saul, *The chemistry of alkenes*, Interscience, London, **1964**; c) Y. Ikeda, T. Nakamura, H. Yorimitsu, K. Oshima, *J. Am. Chem. Soc.* **2002**, *124*, 6514–6515; d) B.-F. Shi, Y.-H. Zhang, J. K. Lam, D.-H. Wang, J.-Q. Yu, *J. Am. Chem. Soc.* **2010**, *132*, 460–461; e) S. Rakshit, C. Grohmann, T. Besset, F. Glorius, *J. Am. Chem.*

- Soc.* **2011**, *133*, 2350–2353; f) K. J. Stowers, K. C. Fortner, M. S. Sanford, *J. Am. Chem. Soc.* **2011**, *133*, 6541–6544; g) M. E. Weiss, L. M. Kreis, A. Lauber, E. M. Carreira, *Angew. Chem. Int. Ed.* **2011**, *50*, 11125–11128; *Angew. Chem.* **2011**, *123*, 11321–11324; h) T. W. Liwosz, S. R. Chemler, *J. Am. Chem. Soc.* **2012**, *134*, 2020–2023.
- [10] Recently, the silver-mediated methoxycarbonyltetrafluoroethylation of arenes was reported; see: A. Hafner, T. J. Feuerstein, S. Bräse, *Org. Lett.* **2013**, *15*, 3468–3471.
- [11] a) B. Gao, Y. Zhao, M. Hu, C. Ni, J. Hu, *Chem. Eur. J.* **2014**, *20*, 7803–7810; b) Y. Zhao, W. Huang, L. Zhu, J. Hu, *Org. Lett.* **2010**, *12*, 1444–1447.
- [12] a) D. A. Wilson, C. J. Wilson, C. Moldoveanu, A.-M. Resmerita, P. Corcoran, L. M. Hoang, B. M. Rosen, V. Percec, *J. Am. Chem. Soc.* **2010**, *132*, 1800–1801; b) T. Ogata, J. F. Hartwig, *J. Am. Chem. Soc.* **2008**, *130*, 13848–13849; c) M. A. Fernández-Rodríguez, Q. Shen, J. F. Hartwig, *J. Am. Chem. Soc.* **2006**, *128*, 2180–2181.
- [13] a) T. Umemoto, S. Ishihara, *J. Am. Chem. Soc.* **1993**, *115*, 2156–2164; b) I. Kieltisch, P. Eisenberger, A. Togni, *Angew. Chem. Int. Ed.* **2007**, *46*, 754–757; *Angew. Chem.* **2007**, *119*, 768–771; c) A. E. Allen, D. W. C. MacMillan, *J. Am. Chem. Soc.* **2010**, *132*, 4986–4987; d) P. V. Pham, D. A. Nagib, D. W. C. MacMillan, *Angew. Chem. Int. Ed.* **2011**, *50*, 6119–6122; *Angew. Chem.* **2011**, *123*, 6243–6246; e) P. Novák, A. Lishchynskyi, V. V. Grushin, *J. Am. Chem. Soc.* **2012**, *134*, 16167–16170; f) R. Tomita, Y. Yasu, T. Koike, M. Akita, *Angew. Chem. Int. Ed.* **2014**, *53*, 7144–7148; *Angew. Chem.* **2014**, *126*, 7272–7276.
- [14] G. K. S. Prakash, R. Krishnamurti, G. A. Olah, *J. Am. Chem. Soc.* **1989**, *111*, 393–395.
- [15] a) M. M. Lerch, B. Morandi, Z. K. Wickens, R. H. Grubbs, *Angew. Chem. Int. Ed.* **2014**, *53*, 8654–8658; *Angew. Chem.* **2014**, *126*, 8798–8862; b) S. Okusu, Y. Sugita, E. Tokunaga, N. Shibata, *Beilstein J. Org. Chem.* **2013**, *9*, 2189–2193, and references therein.
- [16] T. Suzuki, T. Hamura, K. Suzuki, *Angew. Chem. Int. Ed.* **2008**, *47*, 2248–2252; *Angew. Chem.* **2008**, *120*, 2280–2284.
- [17] a) Y. Ozoe, M. Asahi, F. Ozoe, K. Nakahira, T. Mita, *Biochem. Biophys. Res. Commun.* **2010**, *391*, 744–749; b) K. Matoba, H. Kawai, T. Furukawa, A. Kusuda, E. Tokunaga, S. Nakamura, M. Shiro, N. Shibata, *Angew. Chem. Int. Ed.* **2010**, *49*, 5762–5766; *Angew. Chem.* **2010**, *122*, 5898–5902.
- [18] X. Zhu, Y.-F. Wang, W. Ren, F.-L. Zhang, S. Chiba, *Org. Lett.* **2013**, *15*, 3214–3217.
- [19] a) T. W. Liwosz, S. R. Chemler, *Chem. Eur. J.* **2013**, *19*, 12771–12777; b) K. Tsuchii, M. Imura, N. Kamada, T. Hirao, A. Ogawa, *J. Org. Chem.* **2004**, *69*, 6658–6665.
- [20] a) W. T. Miller, R. J. Burnard, *J. Am. Chem. Soc.* **1968**, *90*, 7367–7368; b) W. Tyrre, D. Naumann, *J. Fluorine Chem.* **2004**, *125*, 823–830; c) A. Hafner, N. Jung, S. Bräse, *Synthesis* **2014**, 1440–1447.