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Photo/Ni dual-catalyzed radical defluorinative sulfonylation to synthesize *gem*-difluoro allylsulfones†

 Yiran Xu, Shengchun Wang, Zhao Liu, Mian Guo* and Aiwen Lei *

Radical defluorinative functionalization of α -trifluoromethyl styrenes represents an effective way toward *gem*-difluoroalkenes. There are general interests in developing novel synthetic protocols for defluorinative functionalization with various types of radicals. However, reports on the preparation of *gem*-difluoro allylsulfones via an *S*-centered radical pathway are limited. Herein, we developed a photo/nickel dual-catalyzed defluorinative sulfonylation that rapidly and reliably synthesizes *gem*-difluoro allylsulfones. The merit of this protocol is exhibited by its mild conditions and wide scope, thus providing a novel strategy for the sulfonyl radical participating in radical defluorinative coupling.

As a type of carbonyl isostere, *gem*-difluoroalkenes are usually of unique metabolic stability, bioactivity, and target specificity, thus providing more opportunities for drug discovery (Scheme 1).¹ Therefore, the synthesis of *gem*-difluoroalkenes has recently been an emerging goal in organic and medicinal chemistry. Until now, several strategies have been developed for the preparation of *gem*-difluoroalkenes. Classic methods, such as Wittig-type and Reformatsky decarboxylation reactions, usually involve highly reactive species and/or harsh conditions, and result in a limited compatibility of functional groups. As a convergent approach, S_N2 -type reactions, in which fluoride is lost by nucleophilic attack on CF_3 , require strong nucleophiles and may limit their substrate scope.² Distinctive in mechanisms, the revival of radical chemistry has provided new opportunities to prepare *gem*-difluoroalkenes, in which the defluorination of CF_3 is achieved by a Ni/Cr-promoted β -F elimination³ (Scheme 2A) or a photo-/electro-induced radical/polar cross-cover⁴ (Scheme 2B). However, most studies of radical defluorinative coupling are focused on *C*-centered radicals or *B*-centered radicals (Scheme 2B). The exploration of other types

of radicals to synthesize diversified *gem*-difluoroalkenes is in crucial demand, yet challenging.

Due to the unique properties of the C–S bond, the construction of *S*-containing compounds has drawn much attention from synthetic chemists over recent decades.⁵ Among these organic sulfur compounds, allylsulfones serve as versatile synthetic blocks and can be effectively transformed to other value-added chemicals.⁶ Thus, we became interested in the synthesis of *gem*-difluoro allylsulfones which have the potential to integrate the nature of both *gem*-difluoro alkenes and allylsulfones. However, the synthesis of *gem*-difluoro allylsulfones via an *S*-centered radical pathway remains elusive. Challenges still exist in such desired transformations. Defluorinative sulfonylation to synthesize *gem*-difluoro allylsulfones is endergonic by 17.9 kcal mol^{−1}, which is thermodynamically unfeasible. In addition, an aerobic difunctionalization to produce functionalized CF_3 -substituted tertiary alcohol is exergonic by −1.2 kcal mol^{−1}, which is thermodynamically spontaneous (see the detailed DFT calculation in Fig. S1, ESI†).

To address such a thermodynamic challenge, we focused our attention to the photocatalytic organic reaction that utilizes visible light as energy input, providing a green and sustainable


 Scheme 1 Representative *gem*-difluoroalkenes with biological activity.

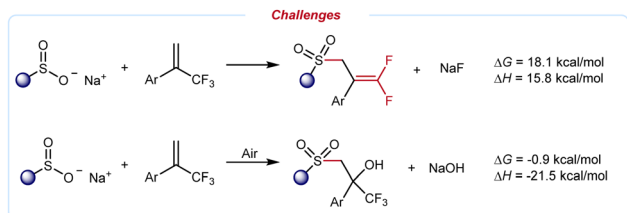
 College of Chemistry and Molecular Sciences, The Institute for Advanced Studies (IAS), Wuhan University, Wuhan 430072, P. R. China.
 E-mail: aiwenlei@whu.edu.cn, whguomian@whu.edu.cn

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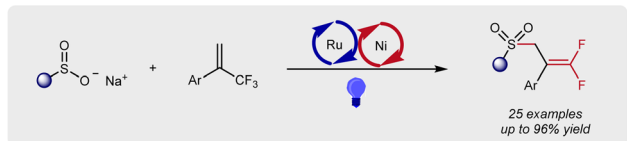
A. Ni-catalyzed radical defluorinative coupling

radical precursor RP = X, OR, CO₂NPhth etc.

B. Photo-induced radical defluorinative coupling



C. This work



Scheme 2 Recent advances in radical defluorinative functionalization to synthesize gem-difluoroalkenes. (A) Ni catalyzed radical defluorinative coupling. (B) Photo-induced radical defluorinative coupling. (C) Outline of this work.

synthetic protocol. Merging photocatalysis and nickel catalysis, we considered that a radical defluorinative coupling could be achieved based on the addition of a sulfonyl radical to α -(trifluoromethyl)-styrenes, where the subsequent β -F elimination could be effectively promoted by a nickel catalyst (Scheme 2C). This dual-catalyzed process would offer a solution to avoid a fast side reaction that leads to α -trifluoromethyl- β -sulfonyl tertiary alcohols with trace air. Herein, we report the successful execution of this design plan.

At the outset of our investigation, we chose 1-methoxy-4-(3,3,3-trifluoroprop-1-en-2-yl)benzene **1a** as the radical acceptor and inexpensive sodium benzenesulfinate **2a** as the sulfonyl radical precursor (Table 1). The initial examination was focused on the ligands with Ru(bpy)₃(PF₆)₂ as the photocatalyst and NiCl₂ as the metal catalyst (entries 1–4). To our delight, the desired transformation was successfully realized in 93% isolated yield with 30 mol% **L2** as ligand. By merging Ru(bpy)₃(PF₆)₂ and Ni(bpy)₃Cl₂, the best results were found in MeCN under blue LED irradiation at room temperature to obtain **3a** in 96% GC yield and 90% isolated yield. Control experiments (entries 6–9) proved that Ru(bpy)₃(PF₆)₂, Ni(bpy)₃Cl₂ and irradiation were essential for this organic transformation. Without the nickel catalyst, only a trace amount of product

Table 1 Optimization of reaction conditions^a

Entry	Variation from the standard conditions ^a	Yield ^b [%]
1	L1 was used	21
2	L2 was used	93
3	L3 was used	65
4	L4 was used	36
5	10 mol% Ni(bpy) ₃ Cl ₂ was used	96 (90)
6	Without ligand	39
7	Without Ru(bpy) ₃ (PF ₆) ₂	n.d.
8	Without Ni(bpy) ₃ Cl ₂	Trace
9	Without irradiation	n.d.
10	Eosin Y as photocatalyst	n.d.
11	[Ir(dFCF ₃ ppy) ₂ ((4,4'-dCF ₃ bpy))](PF ₆) as photocatalyst	12
12	DCE as solvent	21
13	THF as solvent	n.d.
14	Air instead of N ₂	n.d.

^a Conditions: **1a** (0.15 mmol, 1.0 equiv.), **2a** (0.20 mmol, 1.33 equiv.), Ru(bpy)₃(PF₆)₂ (1.5 mol%), NiCl₂ (10 mol%), ligand (30 mol%) in MeCN (2.0 mL) under N₂ atmosphere and irradiation with blue LED (465 nm) for 6 h. ^b Yields were determined by GC-FID with decane as the internal standard; isolated yield is shown in parentheses.

could obtain and the yield was lowered to 39% without the bipyridine ligand. When using eosin Y or an iridium complex as photocatalysts instead of Ru(bpy)₃(PF₆)₂, lower yields of **3a** were found (entries 10 and 11). This transformation exhibited a much lower yield with DCE as the solvent and failed with THF as the solvent (entries 12 and 13). Similar to other radical defluorinative couplings, the synthesis of gem-difluoro allylsulfones failed in air (entry 14).

With the optimal conditions in hand, we turned our attention to exploring the generality of our photo/Ni dual-catalyzed radical defluorinative coupling of α -trifluoromethyl styrene. As shown in Scheme 3, the scope was largely insensitive to electronic changes at the *para* and *meta* positions of trifluoromethylated alkenes (**3a–3k**). However, this defluorinative coupling failed with *ortho*-substituted trifluoromethylated alkenes (see the ESI[†]). Interestingly, other cyclic motifs of CF₃-substituted alkenes were also suitable radical acceptors for this organic transformation, including naphthalene (**3l**), benzodioxole (**3m**), benzodioxan (**3n**), and *N*-Boc pyrrole (**3o**).

Next, the scope of the sodium sulfonates was examined. A series of *para*-substituted sodium benzenesulfonates, including halides (**3q** and **3r**), amides (**3t**), and trifluoromethyl (**3u**), were all well tolerated, forming the desired products in 54–80% yield. In addition, 2-naphthylsulfonic acid sodium (**3v**) was also a suitable sulfonyl radical precursor for this transformation, providing 64% yield. Pleasingly, sodium alkylsulfonates (**3w–3y**) were also well-tolerated under the reaction conditions and provided yields of 59–94%. To further explore the potential applications of this synthetic



Scheme 3 Scope of substrates. Reaction conditions: **1** (0.15 mmol, 1.0 equiv.), **2** (0.2 mmol, 1.33 equiv.), Ru(bpy)₃(PF₆)₂ 1.5 mol%, Ni(bpy)₃Cl₂ 10 mol%, MeCN (2.0 mL), room temperature, N₂, 6 h. Yields of isolated products are shown.

method, we carried out a gram-scale experiment (Scheme 4). The gram-scale reaction between **1a** and **2a** afforded the corresponding gem-difluoroalkenes **3a** in 96% isolated yield.

Based on previous reports,^{4h,7} a plausible mechanism of this radical defluorinative sulfonylation is shown in Scheme 4. Firstly, sodium benzenesulfonate is preferentially oxidized by photo-excited Ru^{II}(bpy)₃ to generate the corresponding sulfonyl radical and Ru^I complex. Then, radical addition occurs between the sulfonyl radical and **2a** to form a benzyl carbon radical **I**, which can further react with Ni^{II} to form alkyl-Ni^{III} species **II**. Next, the final product **3a** is obtained *via* a β-F elimination from **II**, and at the same time Ni^{III}-F is generated. Finally, Ru^{II}(bpy)₃ and Ni^{II} are regenerated *via* a single electron transfer between the Ru^I complex and Ni^{III}-F and the catalytic cycle is completed (Scheme 5).



Scheme 4 Gram-scale experiment. **1a** (6 mmol, 1.0 equiv.), **2a** (8 mmol, 1.33 equiv.), Ru(bpy)₃(PF₆)₂ (0.09 mmol, 1.5 mol%), Ni(bpy)₃Cl₂ (0.6 mmol, 10 mol%), 80 mL CH₃CN, r.t., 465 nm, 12 h.



Scheme 5 Proposed mechanism.

We have demonstrated that a radical defluorinative sulfonylation, consisting of the addition of a sulfonyl radical to alkenes and a nickel-promoted β-F elimination, leads to a challenging coupling of sodium sulfinites and CF₃-substituted alkenes to synthesize a series of *gem*-difluoro allylsulfones. This protocol features mild conditions, a facile synthesis, and a wide scope of substrates. We believe that this method not only provides a rare example of a sulfonyl radical participating in the synthesis of *gem*-difluoro allylsulfones, but also represents a new strategy of photo/nickel dual-catalyzed defluorinative functionalization.

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Conflicts of interest

There are no conflicts to declare.

Notes and references

- (a) M. Bobek, I. Kawai and E. De Clercq, *J. Med. Chem.*, 1987, **30**, 1494; (b) C. Leriche, X. He, C. W. Chang and H. W. Liu, *J. Am. Chem. Soc.*, 2003, **125**, 6348; (c) K. Fujii, Y. Nakamoto, K. Hatan and Y. Kanetsuki, JP2006016331 A, 2006; (d) Y. Pan, J. Qiu and R. B. Silverman, *J. Med. Chem.*, 2003, **46**, 5292; (e) G. Magueur, B. Crousse, M. Ourévitch, D. Bonnet-Delpon and J.-P. Bégue, *J. Fluorine Chem.*, 2006, **127**, 637.
- (a) G. Chelucci, *Chem. Rev.*, 2012, **112**, 1344; (b) X. Zhang and S. Cao, *Tetrahedron Lett.*, 2017, **58**, 375; (c) M. Hu, Z. He, B. Gao, L. Li, C. Ni and J. Hu, *J. Am. Chem. Soc.*, 2013, **135**, 17302; (d) M. Wang, X. Pu, Y. Zhao, P. Wang, Z. Li, C. Zhu and Z. Shi, *J. Am. Chem. Soc.*, 2018, **140**, 9061; (e) P. H. S. Paioti, J. Del Pozo, M. S. Mikus, J. Lee, M. J. Koh, F. Romiti, S. Torker and A. H. Hoveyda, *J. Am. Chem. Soc.*, 2019, **141**, 19917.
- (a) Y. Lan, F. Yang and C. Wang, *ACS Catal.*, 2018, **8**, 9245; (b) Z. Lin, Y. Lan and C. Wang, *ACS Catal.*, 2018, **9**, 775; (c) X. Lu, X. X. Wang, T. J. Gong, J. J. Pi, S. J. He and Y. Fu, *Chem. Sci.*, 2019, **10**, 809;

- (d) C. Zhu, Z. Y. Liu, L. Tang, H. Zhang, Y. F. Zhang, P. J. Walsh and C. Feng, *Nat. Commun.*, 2020, **11**, 4860; (e) C. Zhang, Z. Lin, Y. Zhu and C. Wang, *J. Am. Chem. Soc.*, 2021, **143**, 11602; (f) Y. Ping, Q. Pan, Y. Guo, Y. Liu, X. Li, M. Wang and W. Kong, *J. Am. Chem. Soc.*, 2022, **144**, 11626.
- 4 (a) T. Fujita, K. Fuchibe and J. Ichikawa, *Angew. Chem., Int. Ed.*, 2019, **58**, 390; (b) F.-L. Qing, X.-Y. Liu, J.-A. Ma, Q. Shen, Q. Song and P. Tang, *CCS Chem.*, 2022, **4**, 2518; (c) F. Tian, G. Yan and J. Yu, *Chem. Commun.*, 2019, **55**, 13486; (d) W. Xu, H. Jiang, J. Leng, H. W. Ong and J. Wu, *Angew. Chem., Int. Ed.*, 2020, **59**, 4009; (e) T. Xiao, L. Li and L. Zhou, *J. Org. Chem.*, 2016, **81**, 7908; (f) S. B. Lang, R. J. Wiles, C. B. Kelly and G. A. Molander, *Angew. Chem., Int. Ed.*, 2017, **56**, 15073; (g) J. P. Phelan, S. B. Lang, J. Sim, S. Berritt, A. J. Peat, K. Billings, L. Fan and G. A. Molander, *J. Am. Chem. Soc.*, 2019, **141**, 3723; (h) L.-H. Wu, J.-K. Cheng, L. Shen, Z.-L. Shen and T.-P. Loh, *Adv. Synth. Catal.*, 2018, **360**, 3894; (i) W. J. Yue, C. S. Day and R. Martin, *J. Am. Chem. Soc.*, 2021, **143**, 6395; (j) W. Chen, S. Ni, Y. Wang and Y. Pan, *Org. Lett.*, 2022, **24**, 3647; (k) X. Yan, S. Wang, Z. Liu, Y. Luo, P. Wang, W. Shi, X. Qi, Z. Huang and A. Lei, *Sci. China: Chem.*, 2022, **65**, 762; (l) C. Zhu, M. M. Sun, K. Chen, H. Liu and C. Feng, *Angew. Chem., Int. Ed.*, 2021, **60**, 20237; (m) Z. Cai, R. Gu, W. Si, Y. Xiang, J. Sun, Y. Jiao and X. Zhang, *Green Chem.*, 2022, **24**, 6830; (n) F. Li, C. Pei and R. M. Koenigs, *Angew. Chem., Int. Ed.*, 2022, **61**, e202111892; (o) B. Wang, C. T. Wang, X. S. Li, X. Y. Liu and Y. M. Liang, *Org. Lett.*, 2022, **24**, 6566; (p) X. Wang, C. Wang and C. Bolm, *Org. Lett.*, 2022, **24**, 7461.
- 5 (a) P. Chauhan, S. Mahajan and D. Enders, *Chem. Rev.*, 2014, **114**, 8807; (b) C. Shen, P. Zhang, Q. Sun, S. Bai, T. S. Hor and X. Liu, *Chem. Soc. Rev.*, 2015, **44**, 291; (c) H. Yi, G. Zhang, H. Wang, Z. Huang, J. Wang, A. K. Singh and A. Lei, *Chem. Rev.*, 2017, **117**, 9016; (d) P. Renzi, E. Azzi, A. Lanfranco, R. Moro and A. Deagostino, *Synthesis*, 2021, 3440.
- 6 (a) A. El-Awa, M. N. Noshi, X. M. du Jourdin and P. L. Fuchs, *Chem. Rev.*, 2009, **109**, 2315; (b) X. Chen, S. Hussain, S. Parveen, S. Zhang, Y. Yang and C. Zhu, *Curr. Med. Chem.*, 2012, **19**, 3578.
- 7 (a) Q. Liu and L.-Z. Wu, *Natl. Sci. Rev.*, 2017, **4**, 359; (b) A. Y. Chan, I. B. Perry, N. B. Bissonnette, B. F. Buksh, G. A. Edwards, L. I. Frye, O. L. Garry, M. N. Lavagnino, B. X. Li, Y. Liang, E. Mao, A. Millet, J. V. Oakley, N. L. Reed, H. A. Sakai, C. P. Seath and D. W. C. MacMillan, *Chem. Rev.*, 2022, **122**, 1485; (c) Z. Li, C. Li, Y. Ding and H. Huo, *Coord. Chem. Rev.*, 2022, **460**, 214479; (d) T. Ichitsuka, T. Fujita and J. Ichikawa, *ACS Catal.*, 2015, **5**, 5947; (e) F. Chen, X. Xu, Y. He, G. Huang and S. Zhu, *Angew. Chem., Int. Ed.*, 2020, **59**, 5398; (f) C. Yao, S. Wang, J. Norton and M. Hammond, *J. Am. Chem. Soc.*, 2020, **142**, 4793; (g) J. S. Lin, X. Y. Dong, T. T. Li, N. C. Jiang, B. Tan and X. Y. Liu, *J. Am. Chem. Soc.*, 2016, **138**, 9357.