OL Organic Letters

pubs.acs.org/OrgLett Letter

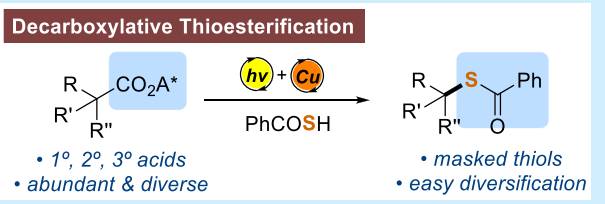
Decarboxylative Thiolation of Redox-Active Esters to Thioesters by Merging Photoredox and Copper Catalysis

Tianxiao Xu, Tianpeng Cao, Mingcheng Yang, Ruting Xu, Xingliang Nie, and Saihu Liao*

Cite This: https://dx.doi.org/10.1021/acs.orglett.0c01180 Read Online

ACCESS | Metrics & More | Article Recommendations | Supporting Information

ABSTRACT: Thioesters and related thiols are critically important to biological systems and also widely employed in the synthesis of pharmaceutically important molecules and polymeric materials. However, known synthetic methods often suffer from the disadvantage of being specific only to certain substrates. Herein, we describe a facile decarboxylative thioesterification of alkyl acid derived redox-active esters by merging photoredox catalysis and copper catalysis. This reaction is applicable to a wide range of carboxylic acids, as well as natural products and drugs, allowing for the synthesis of various thioesters with diverse structures, including tertiary ones that are not accessible via traditional nucleophilic substitution from tertiary halides. Moreover, product utilization is demonstrated with a direct transformation of thioesters to sulfonyl fluorides.



Thioesters and related thiols widely exist in nature and biological systems,[1] and they are also extensively employed for the synthesis of sulfur-containing drugs and polymer materials.[2,3] In the past decades, the thiolation chemistry has been a prominent and active branch of synthetic organic chemistry.[3,4] However, even though many methods are known for thioester and thiol synthesis, they often suffer from the disadvantage of being specific only to certain substrates. For example, the traditional nucleophilic substitution reaction of alkyl halides with sulfur nucleophiles is one of the most employed methods, but failed when applied to tertiary halides due to the steric hindrance and the competing elimination reaction.[5] Recently, alkyl carboxylic acid derived redox-active esters (RAEs), such as *N*-hydroxyphthalimide (NHPI, A*) esters, have been recognized as ideal type of alkyl radical precursors for synthesis, by virtue of their wide availability and structural diversity.[6] Accordingly, a large number of decarboxylative C(sp3)−C and C(sp3)−X (e.g., B, N, O, F etc.) bond formation reactions have been developed in the past years.[6−10] And the corresponding decarboxylative thiolation reactions[9,10] have also been reported, including earlier studies by Barton in the 1980s (Figure 1a).[10] However, the pyridine or aryl groups in the thioether products are difficult to remove to release the corresponding alkyl free thiols, impeding further diversification to other important thiol derivatives.

As a continuum of our effort on the development of diversity-oriented decarboxylative reactions,[11a] we became interested in transferring the structural diversity of abundant carboxylic acids to thioesters, which are regarded as masked thiols[1] and can be readily converted to various pharmaceutically important groups such as sulfides, sulfonamides, and sulfonyl fluorides.[2] And, an advantage of the radical decarboxylative thiolation over traditional nucleophilic substitution reactions that can be expected is the ability to utilize tertiary carboxylic acids.[9] However, in our initial trials on the decarboxylative thioesterification with thiobenzoic acid under Fu's reaction conditions[9b] for decarboxylative thiolation or the conditions for a photoinduced deaminative thiolation,[11b] we only observed a trace

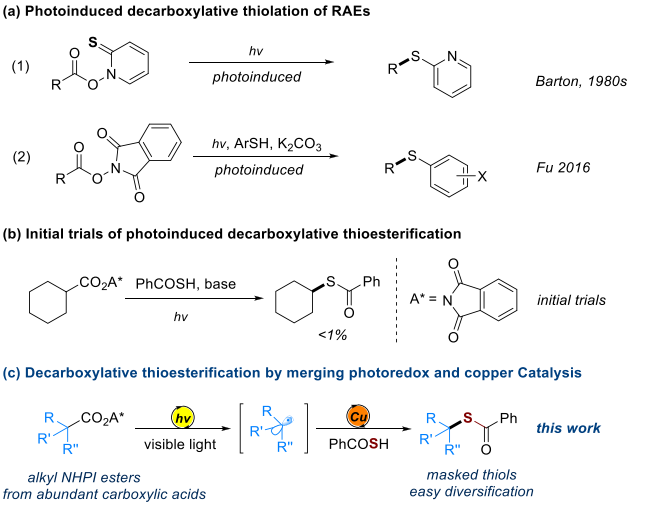


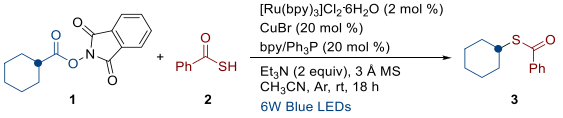
Figure 1. Photoinduced decarboxylative thiolation to sulfides (previous work) and thioesters (this work).

Received: April 2, 2020

amount of the desired thioester product (Figure 1b), suggesting the reactivity of thioacids (RCOSH) might be substantially different from aryl thiols (ArSH). Therefore, we decided to integrate a copper catalytic cycle[12] into this transformation to facilitate the C−S bond formation step. Herein, we report our efforts toward this goal and the invention of an efficient decarboxylative thioesterification reaction of redox-active esters by merging photoredox catalysis and copper catalysis (Figure 1c). This reaction is applicable to a wide range of carboxylic acids, including primary, secondary, and tertiary carboxylic acids, as well as natural products and several pharmaceuticals. In addition, the product utilization has been further demonstrated in a direct transformation of thioesters to sulfonyl fluorides, which are highly in demand recently in the related study in chemical biology and molecular pharmacology.[13]

We commenced our study by using cyclohexanecarboxylic acid derived redox-active ester (**1**) as the model substrate and commercially available thiobenzoic acid (**2**) as the sulfur source (Table 1). After an extensive screening of photocatalyst, copper

Table 1. Reaction Conditions for Decarboxylative Thioesterification[a]



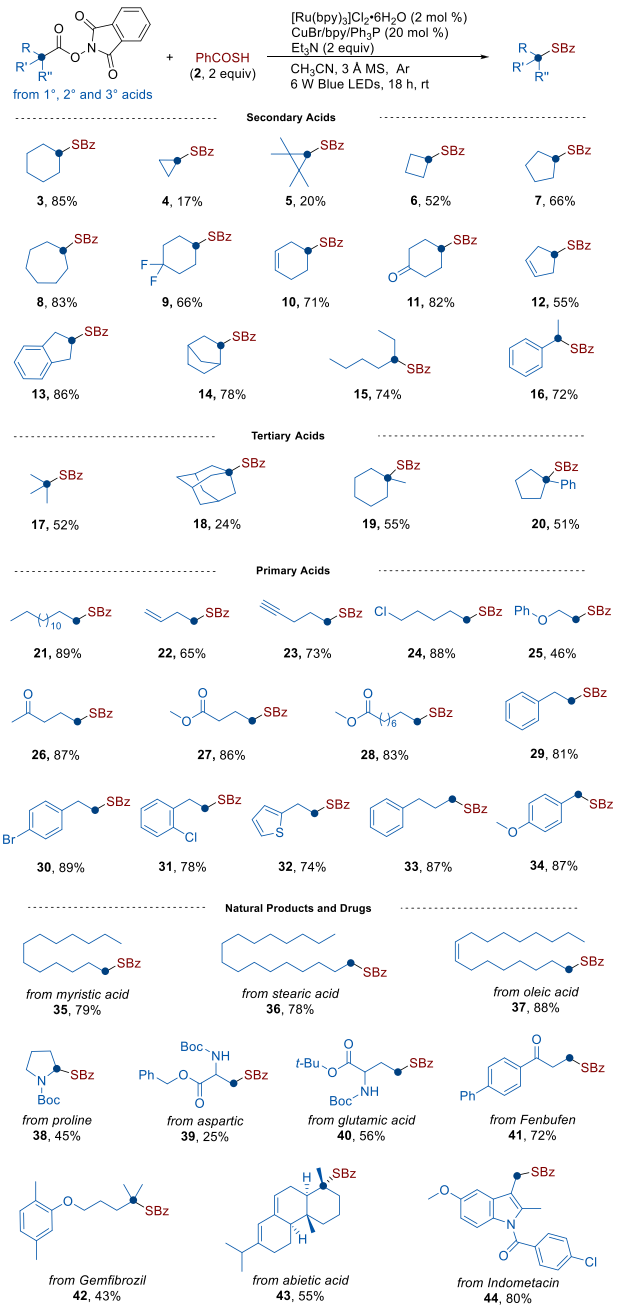
entry	variations from the standard conditions	yield[b]
1	none	86%
2	No light	N.R.
3	No CuBr	trace
4	No Et_3N	16%
5	No $Ru(bpy)_3Cl_2·H_2O$	46%
6	No bpy	52%
7	No Ph_3P	63%
8	No 3 Å MS	72%

[a]Reaction conditions: 0.05 mmol scale in MeCN (0.5 mL), rt, under the irradiation of 6 W blue LEDs. [b]Determined by ^1H NMR with benzyl ether as an internal standard. N.R. = no reaction.

salt, ligand, solvent, base, light source, component ratio, etc. (for details, please see the Supporting Information), a high yield was finally accomplished for this decarboxylative thioesterification by using $[Ru(bpy)_3]Cl_2·6H_2O$ as the photocatalyst and CuBr as the copper catalyst with bipyridine/triphenyl phosphine (bpy/Ph_3P) as the ligands, in the presence of blue light irradiation (Table 1, entry 1). The light proved to be critical to this transformation. No reaction was observed when the reaction was carried out in the dark (entry 2). Among the copper salts screened,[14] CuBr is crucial and gave the highest yields (entry 3). Without triethylamine (Et_3N) or $[Ru(bpy)_3]Cl_2·6H_2O$, the reactions became slow and yields dramatically dropped to 16% and 46%, respectively. Notably, a range of common nitrogen and oxygen ligands were examined[14] aiming to improve the yield of the desired product **3**, and the combination of bpy and Ph_3P was found to give a clean reaction and the highest yield (entry 6 and 7 vs entry 1). The addition of molecular sieves (MS) is also beneficial, which can suppress the hydrolysis of the product (entry 8).

With the catalytic system successfully established, we next examined the reaction scope with a variety of primary, secondary, and tertiary acids (Scheme 1). The model reaction proceeded well on 0.2 mmol scale, giving desired thioester **3** in

Scheme 1. Substrate Scope[a]



[a]Reactions were performed on 0.2 mmol scale, and all yields represent isolated yields.

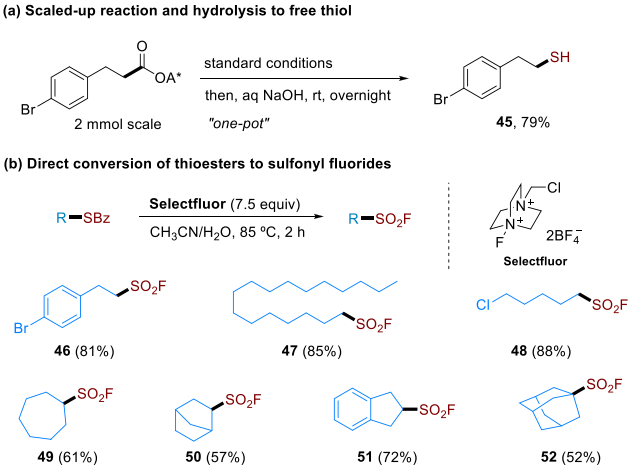
85% isolated yield. Other cyclic carboxylic acids with different ring sizes (**4**−**14**), including cyclopropane (**4** and **5**), cyclobutane (**6**), cyclopentane (**7**), and cycloheptane (**8**), are also suitable substrates. Notably, cyclic substrates with fluoride substitution (**9**), a C−C double bond on the ring (**10** and **12**), a ketone carbonyl group (**11**), and also a bridge cycle (**14**) all reacted well under the standard conditions. Acyclic secondary carboxylic acids (**15** and **16**) also reacted well with thiobenzoic acid. Notably, tertiary acids such as simple pivalic acid (**17**) and adamantane-1-carboxylic acid (**18**) are also suitable substrates, including those with the carboxylic acid group at the five- and six-membered ring site (**19** and **20**), which are difficult to synthesize via traditional nucleophilic substitution from tertiary

https://dx.doi.org/10.1021/acs.orglett.0c01180
Org. Lett. XXXX, XXX, XXX−XXX

halides. In cases of primary acids, we could see a good functional group tolerance to C−C double bond (**22**) or triple bond (**23**), chloride (**24**), ether linker (**25**), ketone (**26**), and also ester (**27** and **28**). Dihydrocinnamic acids (**29**−**31**) and the acids with one carbon extension (**33**) or abridged (**34**) also reacted well. To our delight, this decarboxylative thioesterification can be well applied to the modification of naturally occurring carboxylic acids and several drugs (**35**−**44**). The transformation of amino acid proline gave the thioester (**38**) in 45% isolated yield, while the side-chain carboxylic acid group of aspartic acid and glutamic acid could also be modified (**39** and **40**). Furthermore, the carboxylic groups of drugs such as Fenbufen (**41**), Gemfibrozil (**42**), and Indometacin (**44**) could be transformed readily to the corresponding thioesters in good to high yields. As outlined in Scheme 1, under this tandem photoredox and copper catalytic system, various primary, secondary, and tertiary carbon radicals, including benzylic radicals (**16**, **20**, and **34**) can all be readily generated from the corresponding redox-active esters and coupled subsequently with thiobenzoic acid to afford the desired thioester products, allowing for a facile access to thioesters and their important derivatives[2] with diverse structures.

The past few years have witnessed a fast-growing research activity on the study of sulfonyl fluorides as selective probes in the context of chemical biology and molecular pharmacology.[13] Thiols are important precursors for the synthesis of sulfonyl fluorides.[13a,15] As exemplified in a scaled up reaction (Scheme 2a), the free thiol can be readily obtained upon in situ hydrolysis

Scheme 2. Hydrolysis to Free Thiol and Direct Conversion of Thioesters to Sulfonyl Fluorides



with aq. NaOH after the decarboxylative thioesterification finished. Considering the instability and unpleasant smell of free thiols, we became interested to develop a direct conversion of thioester to sulfonyl fluorides. After examined several reaction conditions, we found that Selectcfluor (chloromethyl-4-fluoro-1,4-diazoniabicyclo [2.2.2] octane bis(tetrafluoroborate)) is a suitable reagent for this goal (Scheme 2, b). With this protocol, primary, secondary, and also tertiary thioesters can be readily converted to the corresponding sulfonyl fluorides (**46**−**52**) in one step.

To gain a better understanding about this decarboxylative thioesterification reaction, we first conducted a radical trapping reaction with TEMPO under the standard conditions, which showed no thioester **3** formed. The cyclohexyl radical generated from the photoinduced decarboxylation was trapped by TEMPO instead (**53**, Figure 2, a), suggesting a radical pathway

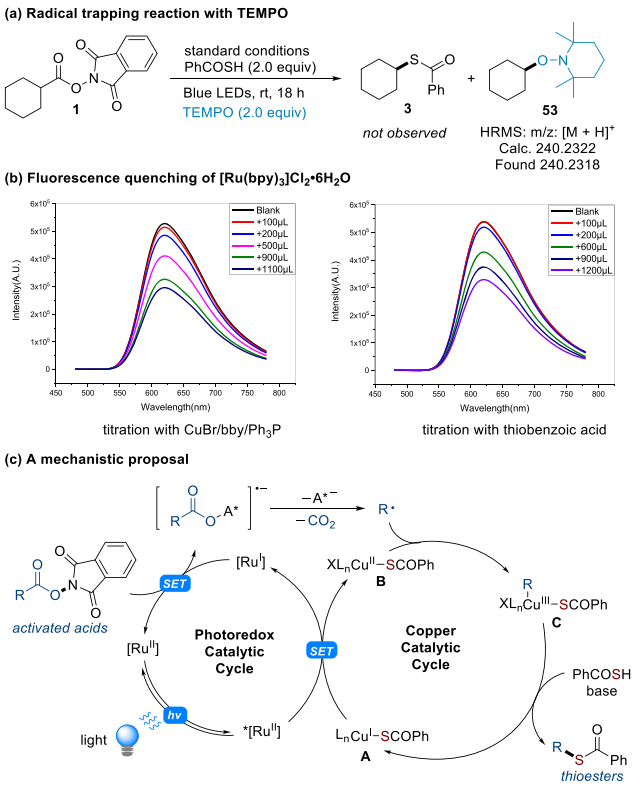


Figure 2. Mechanistic studies and a possible mechanism.

is operative. We next conducted a series of fluorescence quenching experiments with the photocatalyst $[Ru(bpy)_3]Cl_2 \cdot 6H_2O$.[14] Although no apparent fluorescence decrease was observed with either CuBr or bpy/Ph_3P ligand alone, the addition of the CuBr/bpy/Ph_3P combination resulted in a significant fluorescent quenching (Figure 2b, left), indicating the ligand coordination could make the Cu(I) more reducing. In fact, Cu(I) complexes have been reported as a photoredox catalyst able to reduce the redox-active ester via a single electron transfer (SET).[7f,12d,16] Notably, in contrast to the nitrogen or oxygen nucleophiles,[12d−g] the thiobenzoic acid that was found can effectively quench the fluorescence of the excited $[Ru^{II}]$ photocatalyst and, thus, could also act as an electron donor to generate the highly reducing $[Ru^{I}]$ which is required to reduce the NHPI ester. Based on these results and the related mechanistic studies in literature,[12d−g,17] a possible mechanism was outlined in Figure 2c. Under light irradiation, the photocatalyst $[Ru^{II}]$ is first excited and then accepts an electron from $L_nCu(I)$ species (**A**), which can be easily formed from CuBr and thiobenzoic acid by anion exchange in the presence of base,[18] to afford the corresponding highly reducing $[Ru^{I}]$ and the key Cu^{II} species (**B**). A single electron transfer from $[Ru^{I}]$ to the redox-active ester delivers the alkyl radical (R·), which can be trapped by Cu^{II} **B** to generate the key intermediate **C**, which then undergoes a reductive elimination to afford the desired thioester products, while the incoming thiobenzoic acid can regenerate **A**. Alternatively, $*[Ru^{II}]$ can be reductively quenched by thiobenzoic acid[17b] to generate $[Ru^{I}]$, and the PhCOS· generated concurrently can be trapped by LnCu(I)X species to form **B** as well (for simplicity, not shown in the catalytic cycle).

https://dx.doi.org/10.1021/acs.orglett.0c01180
Org. Lett. XXXX, XXX, XXX−XXX

In conclusion, by merging photoredox catalysis and copper catalysis, a visible light-mediated decarboxylative thiolation of redox-active esters to thioesters has been successfully developed for the first time. The reaction is applicable to a variety of alkyl carboxylic acids, including primary, secondary, and tertiary ones, as well as several amino acids and drugs, allowing for a facile access to various thioesters and related thiol derivatives, which are important compounds in medicinal and materials chemistry. Moreover, product utilization has be demonstrated with a direct transformation of the thioesters to sulfonyl fluorides. We anticipate that this radical decarboxylative thioesterification will provide a useful, complementary new approach to traditional sp^3 C−S alkylation methods.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.orglett.0c01180.

Experimental procedures and characterization data (PDF)

■ AUTHOR INFORMATION

Corresponding Author

Saihu Liao − *Key Laboratory of Molecule Synthesis and Function Discovery, College of Chemistry, Fuzhou University, Fuzhou 350116, P. R. China; Beijing National Laboratory for Molecular Sciences (BNLMS), Beijing 100190, P. R. China;* orcid.org/0000-0002-0251-8757; Email: shliao@fzu.edu.cn

Authors

Tianxiao Xu − *Key Laboratory of Molecule Synthesis and Function Discovery, College of Chemistry, Fuzhou University, Fuzhou 350116, P. R. China*

Tianpeng Cao − *Key Laboratory of Molecule Synthesis and Function Discovery, College of Chemistry, Fuzhou University, Fuzhou 350116, P. R. China*

Mingcheng Yang − *Key Laboratory of Molecule Synthesis and Function Discovery, College of Chemistry, Fuzhou University, Fuzhou 350116, P. R. China*

Ruting Xu − *Key Laboratory of Molecule Synthesis and Function Discovery, College of Chemistry, Fuzhou University, Fuzhou 350116, P. R. China*

Xingliang Nie − *Key Laboratory of Molecule Synthesis and Function Discovery, College of Chemistry, Fuzhou University, Fuzhou 350116, P. R. China*

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.orglett.0c01180

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We gratefully acknowledge National Natural Science Foundation of China (No. 21602028), Beijing National Laboratory for Molecular Sciences (BNLMS201913), the Recruitment Program of Global Experts, the Hundred-Talent Project of Fujian, and Fuzhou University for the financial support.

■ REFERENCES

(1) (a) Kulkarni, S. S.; Sayers, J.; Premdjee, B.; Payne, R. J. Rapid and efficient protein synthesis through expansion of the native chemical ligation concept. *Nat. Rev. Chem.* **2018**, *2*, 1−17. (b) Bondalapati, S.; Jbara, M.; Brik, A. Expanding the chemical toolbox for the synthesis of large and uniquely modified proteins. *Nat. Chem.* **2016**, *8*, 407. (c) Góngora-Benítez, M.; Tulla-Puche, J.; Albericio, F. Multifaceted Roles of Disulfide Bonds. Peptides as Therapeutics. *Chem. Rev.* **2014**, *114*, 901−926. (d) Cheng, Z.; Zhang, J.; Ballou, D. P.; Williams, C. H., Jr. Reactivity of Thioredoxin as a Protein Thiol-Disulfide Oxidoreductase. *Chem. Rev.* **2011**, *111*, 5768−5783. (e) Kent, S. B. H. Total chemical synthesis of proteins. *Chem. Soc. Rev.* **2009**, *38*, 338−351.

(2) For reviews on drugs, see: (a) Scott, K. A.; Njardarson, J. T. Analysis of US FDA-Approved Drugs Containing Sulfur Atoms. *Top. Curr. Chem.* **2019**, *376* (5), 1−34. (b) Feng, M.; Tang, B.; Liang, S.; Jiang, X. Sulfur Containing Scaffolds in Drugs: Synthesis and Application in Medicinal Chemistry. *Curr. Top. Med. Chem.* **2016**, *16*, 1200−1216. (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: Miniperspective. *J. Med. Chem.* **2014**, *57*, 2832−2842.

(3) (a) Naowarojna, N.; Cheng, R.; Chen, L.; Quill, M.; Xu, M.; Zhao, C.; Liu, P. Mini-Review: Ergothioneine and Ovothiol Biosyntheses, an Unprecedented Trans-Sulfur Strategy in Natural Product Biosynthesis. *Biochemistry* **2018**, *57*, 3309−3325. (b) Dunbar, K. L.; Scharf, D. H.; Litomska, A.; Hertweck, C. Enzymatic Carbon−Sulfur Bond Formation in Natural Product Biosynthesis. *Chem. Rev.* **2017**, *117*, 5521−5577. (c) Dénès, F.; Pichowicz, M.; Povie, G.; Renaud, P. Thiyl Radicals in Organic Synthesis. *Chem. Rev.* **2014**, *114*, 2587−2693. (d) Dreaden, E. C.; Alkilany, A. M.; Huang, X.; Murphy, C. J.; EI-Sayed, M. A. The golden age: gold nanoparticles for biomedicine. *Chem. Soc. Rev.* **2012**, *41*, 2740−2779. (e) Franc, G.; Kakkar, A. K. Click" methodologies: efficient, simple and greener routes to design dendrimers. *Chem. Soc. Rev.* **2010**, *39*, 1536−1544. (f) Hoyle, C. E.; Bowman, C. N. Thiol−Ene Click Chemistry. *Angew. Chem., Int. Ed.* **2010**, *49*, 1540−1573.

(4) For selected recent studies, see: (a) Wang, X.; Wang, B.; Yin, X.; Yu, W.; Liao, Y.; Ye, J.; Wang, M.; Hu, L.; Liao, J. Palladium-Catalyzed Enantioselective Thiocarbonylation of Styrenes. *Angew. Chem., Int. Ed.* **2019**, *58*, 12264−12270. (b) Ouhib, F.; Grignard, B.; van den Broeck, E.; Luxen, A.; Robeyns, K.; van Speybroeck, V.; Jerome, C.; Detrembleur, C. A Switchable Domino Process for the Construction of Novel CO_2-Sourced Sulfur Containing Building Blocks and Polymers. *Angew. Chem.* **2019**, *131*, 11894−11899. (c) Kang, Y. S.; Zhang, P.; Li, M. Y.; Chen, Y. K.; Xu, H. J.; Zhao, J.; Sun, W. Y.; Yu, J. Q.; Lu, Y. Ligand-Promoted Rh^{III}-Catalyzed Thiolation of Benzamides with a Broad Disulfide Scope. *Angew. Chem., Int. Ed.* **2019**, *58*, 9099−9103. (d) Laudadio, G.; Barmpoutsis, E.; Schotten, C.; Struik, L.; Govaerts, S.; Browne, D. L.; Noël, T. Sulfonamide Synthesis through Electrochemical Oxidative Coupling of Amines and Thiols. *J. Am. Chem. Soc.* **2019**, *141*, 5664−5668. (e) Liu, D.; Ma, H.-X.; Fang, P.; Mei, T.-S. Nickel-Catalyzed Thiolation of Aryl Halides and Heteroaryl Halides through Electrochemistry. *Angew. Chem., Int. Ed.* **2019**, *58*, 5033−5037. (f) Yang, X.-H.; Davison, R. T.; Nie, S.-Z.; Cruz, F. A.; McGinnis, T. M.; Dong, V. M. Catalytic Hydrothiolation: Counterion-Controlled Regioselectivity. *J. Am. Chem. Soc.* **2019**, *141*, 3006−3013. (g) Zhang, Y.; Xu, X.; Zhu, S. Nickel-Catalysed Selective Migratory Hydrothiolation of Alkenes and Alkynes with Thiols. *Nat. Commun.* **2019**, *10*, 1752. (h) McKinnell, R. M.; Fatheree, P.; Choi, S.-K.; Gendron, R.; Jendza, K.; Blair, B. O.; Budman, J.; Hill, C. M.; Hegde, L. G.; Yu, C.; McConn, D.; Hegde, S. S.; Marquess, D. G.; Klein, U. Discovery of TD-0212, an Orally Active Dual Pharmacology AT1 Antagonist and Neprilysin Inhibitor (ARNI). *ACS Med. Chem. Lett.* **2019**, *10* (1), 86−91.

(5) Wardell, J. L. In *The Chemistry of the Thiol Group*; Patai, S., Ed.; Wiley: New York, 1974; pt. 1, pp 179−211.

(6) For selected reviews, see: (a) Xuan, J.; Zhang, Z.-G.; Xiao, W.-J. Visible−Light−Induced Decarboxylative Functionalization of Carboxylic Acids and Their Derivatives. *Angew. Chem., Int. Ed.* **2015**, *54*, 15632−15641. (b) Jin, Y.; Fu, H. Visible−Light Photoredox Decarboxylative Couplings. *Asian J. Org. Chem.* **2017**, *6*, 368−385. (c) Schwarz, J.; König, B. Decarboxylative reactions with and without light − a comparison. *Green Chem.* **2018**, *20*, 323−361. (d) Murarka, S.

https://dx.doi.org/10.1021/acs.orglett.0c01180
Org. Lett. XXXX, XXX, XXX−XXX

N−(Acyloxy)phthalimides as Redox−Active Esters in Cross−Coupling Reactions. *Adv. Synth. Catal.* **2018**, *360*, 1735−1753.

(7) For selected recent reports, see: (a) Fawcett, A.; Pradeilles, J.; Wang, Y.; Mutsuga, T.; Myers, E. L.; Aggarwal, V. K. Photoinduced Decarboxylative Borylation of Carboxylic Acids. *Science* **2017**, *357*, 283−286. (b) 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. (c) Wang, D.; Zhu, N.; Chen, P.; Lin, Z.; Liu, G. Enantioselective Decarboxylative Cyanation Employing Cooperative Photoredox Catalysis and Copper Catalysis. *J. Am. Chem. Soc.* **2017**, *139*, 15632−15635. (d) Mao, R.; Frey, A.; Balon, J.; Hu, X. Decarboxylative C (sp_3)−N Cross-Coupling via Synergetic Photoredox and Copper Catalysis. *Nat. Catal.* **2018**, *1*, 120−126. (e) Ma, J.; Lin, J.; Zhao, L.; Harms, K.; Marsch, M.; Xie, X.; Meggers, E. Synthesis of β-Substituted γ-Aminobutyric Acid Derivatives through Enantioselective Photoredox Catalysis. *Angew. Chem., Int. Ed.* **2018**, *57*, 11193−11197. (f) Wang, C.; Guo, M.; Qi, R.; Shang, Q.; Liu, Q.; Wang, S.; Zhao, L.; Wang, R.; Xu, Z. Visible-Light-Driven, Copper Catalyzed Decarboxylative C(sp_3)− H Alkylation of Glycine and Peptides. *Angew. Chem., Int. Ed.* **2018**, *57*, 15841−15846. (g) Proctor, R. S. J.; Davis, H. J.; Phipps, R. J. Catalytic Enantioselective Minisci-Type Addition to Heteroarenes. *Science* **2018**, *360*, 419−422. (h) Fu, M.-C.; Shang, R.; Zhao, B.; Wang, B.; Fu, Y. Photocatalytic Decarboxylative Alkylations Mediated by Triphenylphosphine and Sodium Iodide. *Science* **2019**, *363*, 1429−1434.

(8) (a) Qin, T.; Cornella, J.; Li, C.; Malins, L. R.; Edwards, J. T.; Kawamura, S.; Maxwell, B. D.; Eastgate, M. D.; Baran, P. S. A General Alkyl-Alkyl Cross-Coupling Enabled by Redox-Active Esters and Alkylzinc Reagents. *Science* **2016**, *352*, 801−805. (b) Huihui, K. M. M.; Caputo, J. A.; Melchor, Z.; Olivares, A. M.; Spiewak, A. M.; Johnson, K. A.; DiBenedetto, T. A.; Kim, S.; Ackerman, S. L. K. G.; Weix, D. J. Decarboxylative Cross-Electrophile Coupling of N-hydroxyphthalimide Esters with Aryl Iodides. *J. Am. Chem. Soc.* **2016**, *138*, 5016−5019. (c) Xue, W.; Oestreich, M. Copper-Catalyzed Decarboxylative Radical Silylation of Redox-Active Aliphatic Carboxylic Acid Derivatives. *Angew. Chem., Int. Ed.* **2017**, *56*, 11649−11652. (d) Liu, X.-G.; Zhou, C.-J.; Lin, E.; Han, X.-L.; Zhang, S.-S.; Li, Q.; Wang, H. Decarboxylative Negishi Coupling of Redox−Active Aliphatic Esters by Cobalt Catalysis. *Angew. Chem., Int. Ed.* **2018**, *57*, 13096−13100. (e) Zeng, X. J.; Yan, W. H.; Zacate, S. B.; Chao, T. H.; Sun, X. D.; Cao, Z.; Bradford, K. G. E.; Paeth, M.; Tyndall, S. B.; Yang, K. D.; Kuo, T. C.; Cheng, M. J.; Liu, W. Copper−Catalyzed Decarboxylative Difluoromethylation. *J. Am. Chem. Soc.* **2019**, *141*, 11398−11403.

(9) (a) Wimmer, A.; König, B. Photocatalytic Formation of Carbon−Sulfur Bonds. *Beilstein J. Org. Chem.* **2018**, *14*, 54−83. (b) Jin, Y.; Yang, H.; Fu, H. An N-(acetoxy) phthalimide Motif as a Visible-Light Pro-photosensitizer in Photoredox Decarboxylative Arylthiation. *Chem. Commun.* **2016**, *52*, 12909−12912. (c) Gianatassio, R.; Kawamura, S.; Eprile, C. L.; Foo, K.; Ge, J.; Burns, A. C.; Collins, M. R.; Baran, P. S. Simple Sulfinate Synthesis Enables C-H Trifluoromethylcyclopropanation. *Angew. Chem., Int. Ed.* **2014**, *53*, 9851−9855.

(10) (a) Barton, D. H. R.; Crich, D.; Motherwell, W. B. New and Improved Methods for the Radical Decarboxylation of Acids. *J. Chem. Soc., Chem. Commun.* **1983**, 939−941. (b) Barton, D. H. R.; Crich, D.; Motherwell, W. B. The Invention of New Radical Chain Reactions. Part VIII. Radical Chemistry of Thiohydroxamic Esters; A New Method for the Generation of Carbon Radicals from Carboxylic Acids. *Tetrahedron* **1985**, *41*, 3901−3924. (c) Barton, D. H. R.; Bridon, D.; Fernandaz-Picot, I.; Zard, S. Z. The Invention of Radical Reactions: Part XV. Some Mechanistic Aspects of The Decarboxylative Rearrangement of Thiohydroxamic esters. *Tetrahedron* **1987**, *43*, 2733−2740. (d) Barton, D. H. R.; Lacher, B.; Misterkiewicz, B.; Zard, S. Z. The Invention of Radical Reactions: Part XVII. A Decarboxylative Sulphonylation of Carboxylic Acids. *Tetrahedron* **1988**, *44*, 1153−1158.

(11) (a) Xu, R.; Xu, T.; Yang, M.; Cao, T.; Liao, S. A rapid access to aliphatic sulfonyl fluorides. *Nat. Commun.* **2019**, *10*, 3752. (b) Yang, M.; Cao, T.; Xu, T.; Liao, S. Visible-Light-Induced Deaminative Thioesterification of Amino Acid Derived Katritzky Salts via Electron Donor−Acceptor Complex Formation. *Org. Lett.* **2019**, *21*, 8673−8678.

(12) For reviews, see: (a) Skubi, K. L.; Blum, T. R.; Yoon, T. P. Dual Catalysis Strategies in Photochemical Synthesis. *Chem. Rev.* **2016**, *116*, 10035−10074. (b) Huang, H.; Jia, K.; Chen, Y. Radical Decarboxylative Functionalizations Enabled by Dual Photoredox Catalysis. *ACS Catal.* **2016**, *6*, 4983−4988. (c) Reed, N. L.; Herman, M. I.; Miltchev, V. P.; Yoon, T. P. Tandem Copper and Photoredox Catalysis in Photocatalytic Alkene Difunctionalization Reactions. *Beilstein J. Org. Chem.* **2019**, *15*, 351−356. For selected examples: (d) Zhao, W.; Wurz, R. P.; Peters, J. C.; Fu, G. C. Photoinduced, Copper-Catalyzed Decarboxylative C−N Coupling to Generate Protected Amines: An Alternative to the Curtius Rearrangement. *J. Am. Chem. Soc.* **2017**, *139*, 12153−12156. (e) Mao, R.; Balon, J.; Hu, X. Cross−Coupling of Alkyl Redox−Active Esters with Benzophenone Imines: Tandem Photoredox and Copper Catalysis. *Angew. Chem., Int. Ed.* **2018**, *57*, 9501−9504. (f) Liang, Y.; Zhang, X.; MacMillan, D. W. C. Decarboxylative sp^3 C−N coupling via dual copper and photoredox catalysis. *Nature* **2018**, *559*, 83−88. (g) Mao, R.; Balon, J.; Hu, X. Decarboxylative C (sp3)−O Cross−Coupling. *Angew. Chem., Int. Ed.* **2018**, *57*, 13624−13628.

(13) For reviews on SuFEx Chemistry, see: (a) Dong, J.; Krasnova, L.; Finn, M. G.; Sharpless, K. B. Sulfur (VI) fluoride exchange (SuFEx): another good reaction for click chemistry. *Angew. Chem., Int. Ed.* **2014**, *53*, 9430−9448. (b) Narayanan, A.; Jones, L. H. Sulfonyl fluorides as privileged warheads in chemical biology. *Chem. Sci.* **2015**, *6*, 2650−2659. (c) Barrow, A. S.; Smedley, C. J.; Zheng, Q.; Li, S.; Dong, J.; Moses, J. E. The growing applications of SuFEx click chemistry. *Chem. Soc. Rev.* **2019**, *48*, 4731−4758.

(14) For more details, please see the Supporting Information.

(15) (a) Krutak, J. J.; Burpitt, R. D.; Moore, W. H.; Hyatt, J. A. Chemistry of ethenesulfonyl fluoride. Fluorosulfonylethylation of organic compounds. *J. Org. Chem.* **1979**, *44*, 3847−3858. (b) Wright, S. W.; Hallstrom, K. N. A Convenient preparation of heteroaryl sulfonamides and sulfonyl fluorides from heteroaryl thiols. *J. Org. Chem.* **2006**, *71*, 1080−1084. (c) Laudadio, G.; Bartolomeu, A. d. A.; Verwijlen, L. M. H. M.; Cao, Y.; de Oliveira, K. T.; Noël, T. Sulfonyl fluoride synthesis through electrochemical oxidative coupling of thiols and potassium fluoride. *J. Am. Chem. Soc.* **2019**, *141*, 11832−11836.

(16) (a) Hossain, A.; Bhattacharyya, A.; Reiser, O. Copper's rapid ascent in visible-light photoredox catalysis. *Science* **2019**, *364*, No. eaav9713. (b) Yu, X.-Y.; Zhao, Q.-Q.; Chen, J.; Chen, J.-R.; Xiao, W.-J. Copper−Catalyzed Radical Cross−Coupling of Redox−Active Oxime Esters, Styrenes, and Boronic Acids. *Angew. Chem., Int. Ed.* **2018**, *57*, 15505−15509.

(17) (a) Weng, Z.; He, W.; Chen, C.; Lee, R.; Tan, D.; Lai, Z.; Kong, D.; Yuan, Y.; Huang, K.-W. An Air−Stable Copper Reagent for Nucleophilic Trifluoromethylthiolation of Aryl Halides. *Angew. Chem., Int. Ed.* **2013**, *52*, 1548−1552. (b) Liu, H.; Zhao, L.; Yuan, Y.; Xu, Z.; Chen, K.; Qiu, S.; Tan, H. Potassium thioacids mediated selective amide and peptide constructions enabled by visible light photoredox catalysis. *ACS Catal.* **2016**, *6*, 1732−1736. (c) Soria-Castro, S. M.; Andrada, D. M.; Caminos, D. A.; Argüello, J. E.; Robert, M.; Peñéñory, A. B. Mechanistic insight into the Cu-catalyzed C−S cross-coupling of thioacetate with aryl halides: A joint experimental-computational study. *J. Org. Chem.* **2017**, *82*, 11464−11473.

(18) The addition of thiobenzoic acid to the CuBr/ligand/Et_3N solution led to a quick color change from dark orange to light yellow, and HRMS analysis indicated the bpyCu-SCOPh (m/z 378.9938) formation.

https://dx.doi.org/10.1021/acs.orglett.0c01180
Org. Lett. XXXX, XXX, XXX−XXX