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Copper-Catalyzed Direct C−H Oxidative Trifluoromethylation of Heteroarenes

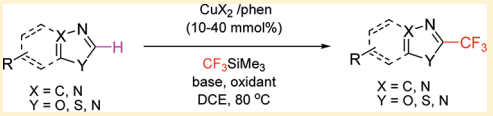
Lingling Chu[†] and Feng-Ling Qing*[,†,‡]

[†]Key Laboratory of Organofluorine Chemistry, Shanghai Institute of Organic Chemistry, Chinese Academy of Science, 345 Lingling Lu, Shanghai 200032, China

[‡]College of Chemistry, Chemical Engineering and Biotechnology, Donghua University, 2999 North Renmin Lu, Shanghai 201620, China

Supporting Information

ABSTRACT: This article describes the copper-catalyzed oxidative trifluoromethylation of heteroarenes and highly electron-deficient arenes with CF_3SiMe_3 through direct C−H activation. In the presence of catalyst $Cu(OAc)_2$, ligand 1,10-phenanthroline and cobases *tert*-BuONa/NaOAc, oxidative trifluoromethylation of 1,3,4-oxadiazoles with CF_3SiMe_3 proceeded smoothly using either air or di-*tert*-butyl peroxide as an oxidant to give the corresponding trifluoromethylated 1,3,4-oxadiazoles in high yields. Di-*tert*-butyl peroxide was chosen as the suitable oxidant for oxidative trifluoromethylation of 1,3-azoles and perfluoroarenes. $Cu(OH)_2$ and Ag_2CO_3 were the best catalyst and oxidant for direct oxidative trifluoromethyaltion of indoles. The optimum reaction conditions enable oxidative trifluoromethylation of a range of heteroarenes that bear numerous functional groups. The prepared trifluoromethylated heteroarenes are of importance in the areas of pharmaceuticals and agrochemicals. The preliminary mechanistic studies of these oxidative trifluoromethylations are also reported.



INTRODUCTION

Trifluoromethylated arenes and heteroarenes are widely applicable in the synthesis of pharmaceuticals and agrochemicals because the strong electron-withdrawing nature and large hydrophobic domain of trifluoromethyl group can dramatically modify the bioavailability and stability of target molecules.[1] As there are no naturally occurring CF_3-containing molecules found in any abundance in nature, a lot of effort has been focused on the trifluoromethylation of arenes and heteroarenes.[2] Conversion of a functional group into the trifluoromethyl group (CF_3-) using SbF_5 or SF_4 is the traditional method for arene trifluoromethylation,[3] but such transformation suffers from harsh reaction conditions and limited substrate scope. The radical[4] and electrophilic[5] trifluoromethylation of arenes and heteroarenes has been also reported, but these methods are often limited to arenes and heteroarenes bearing electron-donating substituents and, in some cases, generate mixtures of regioisomers. Since Mcloughlin and Thrower[6] and Kobayashi and Kumadaki[7] preliminarily reported the trifluoromethylation of aryl iodides in the presence of copper powder more than 40 years ago, and Wiemers and Burton[8] had identified the $CuCF_3$ complex by NMR in 1986, the transition-metal-mediated cross-coupling procedure has become the most promising method for the introduction of trifluoromethyl group into arenes and heteroarenes.[2] Recently, notable breakthrough has been made in palladium-catalyzed trifluoromethylation of aryl halides[9] and aryl C−H bonds.[10] Because of the lower cost compared to palladium, copper has been more extensively employed for the preparation of trifluoromethylated arenes and heteroarenes.[11−13] Typically, aryl iodides and activated aryl bromides were used to couple with the highly reactive intermediate $CuCF_3$.[11,12] Very recently, the copper-mediated trifluoromethylation of aryl and heteroaryl boronic acids with nucleophilic and electrophilic trifluoromethylating reagents has been also developed.[13] Although considerable progress has been made in the development of Cu-mediated trifluoromethylation of arenes and heteroarenes, there is no doubt that the most attractive and ideal route to aryl- or heteroaryl-CF_3 bonds would involve direct trifluoromethylation of C−H bonds of arenes and heteroarenes due to its step economy.

Recently, we have successfully developed the first example of a mild copper-mediated aerobic oxidative trifluoromethylation of terminal alkynes with (trifluoromethyl)trimethylsilane (Ruppert−Prakash reagent, CF_3SiMe_3) (Scheme 1a).[14] Inspired by this work, we envisioned that the copper-mediated direct C−H oxidative trifluoromethylation strategy might be applicable to heteroarenes[15,16] which bear similar acidic C−H bonds as those of terminal alkynes (Scheme 1b). Herein, we

Scheme 1. Copper-Catalyzed Direct C−H Oxidative Trifluoromethylation Strategy

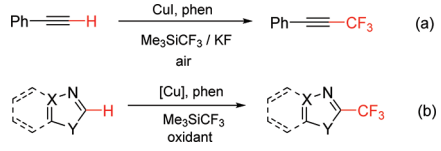


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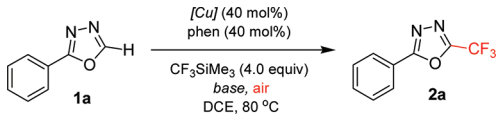
Table 1. Optimization of Copper-Catalyzed Oxidative Trifluoromethylation of 1,3,4-Oxadiazole 1a[a]



entry	copper	base (equiv)	yield (%)[b]
1	CuI	*tert*-BuONa (1.1)	34
2	CuOAc	*tert*-BuONa (1.1)	39
3	$CuCl_2$	*tert*-BuONa (1.1)	12
4	$Cu(OAc)_2$	*tert*-BuONa (1.1)	60
5	$Cu(OAc)_2$	*tert*-BuOLi (1.1)	18
6	$Cu(OAc)_2$	*tert*-BuOK (1.1)	40
7	$Cu(OAc)_2$	K_3PO_4 (1.1)	25
8	$Cu(OAc)_2$	Cs_2CO_3 (1.1)	20
9	$Cu(OAc)_2$	*tert*-BuONa (3.0)	30
10	$Cu(OAc)_2$	*tert*-BuONa (1.1) + NaOAc (3.0)	92 (89)[c]
11	$Cu(OAc)_2$	*tert*-BuONa (1.1) + KF (3.0)	65
12	$Cu(OAc)_2$	*tert*-BuONa (1.1) + CsF (3.0)	58
13[d]	$Cu(OAc)_2$	*tert*-BuONa (1.1) + NaOAc (3.0)	39
14	–	*tert*-BuONa (1.1) + NaOAc (3.0)	–
15[e]	$Cu(OAc)_2$	*tert*-BuONa (1.1) + NaOAc (3.0)	–

[a]Reaction conditions: **1a** (0.2 mmol), CF_3SiMe_3 (0.8 mmol), [Cu] (40 mmol %), 1,10-phenanthroline (40 mmol %), and 4 Å MS (60 mg) in DCE (2.0 mL) at 80 °C for 6 h under air in a sealed tube. [b]Yield was determined by ^{19}F NMR spectroscopy using an internal standard. [c]Isolated yield in the parentheses. [d]The copper loading was reduced to 20 mol %. [e]In the absence of 1,10-phenanthroline.

describe a novel method for copper-catalyzed oxidative trifluoromethylation of heteroarenes and electron-deficient polyfluoroarenes with nucleophilic Me_3SiCF_3 via C−H activation.[17] Mechanistic investigation of this oxidative trifluoromethylation procedure is also described.

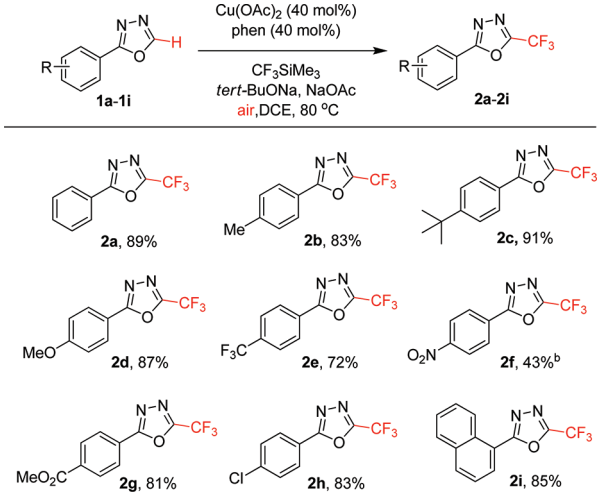
RESULTS AND DISCUSSION

Oxidative Trifluoromethylation of 1,3,4-Oxadiazoles.

We began our oxidative trifluoromethylation studies with 2-phenyl-1,3,4-oxadiazole (**1a**) as a model substrate (Table 1). On the basis of our previous work[14] and relative works on copper-catalyzed direct functionalization of heteroarenes,[16] treatment of **1a** (1.0 equiv) with CF_3SiMe_3 (4.0 equiv), CuI (40 mol %), and 1,10-phenanthroline (phen) (40 mol %) in the presence of *tert*-BuONa (1.1 equiv) under air atmosphere in 1,2-dichloromethane (DCE) at 80 °C provided the desired product **2a** in 34% yield (Table 1, entry 1), in which *tert*-BuONa was served as both the deprotonation reagent of **1a** and the initiator of CF_3SiMe_3.[18] An examination of different copper catalysts showed that $Cu(OAc)_2$ is the most reactive copper source and dramatically increased the yield of **2a** to 60% (Table 1, entries 1−4). Further screening of bases revealed that *tert*-BuONa is the optimal base (entries 4−8). When the amount of *tert*-BuONa was increased to 3.0 equiv, which was supposed to facilitate the conversion of **1a**, however, the yield of **2a** was decreased dramatically and the homocoupling product of **1a** was detected by GC-MS (entry 9). To solve this dilemma, we speculated that combination of a strong base (*tert*-BuONa) and a weak base might be helpful in enhancing the reaction efficiency and inhibiting the homocoupling reaction of **1a**. Accordingly, when NaOAc (3.0 equiv) was employed as the cobase, we were pleased to find that the yield of **2a** was improved to 92% (entry 10). But other bases, such as KF and CsF, had no effects on the reactions (entries 11 and 12). Starting material **1a** was not completely consumed once the loading of copper was reduced to 20 mol % (entry 13). No product was detected in the absence of either $Cu(OAc)_2$ or 1,10-phenanthroline (entries 14 or 15).

With the optimum reaction conditions in hand, we investigated the scope of this C−H oxidative trifluoromethylation. A variety of different 2-aryl substituted 1,3,4-oxadiazoles had been employed under the same reaction condition, as indicated in entry 10 of Table 1, and the results were summarized in Table 2. The reactions were compatible with both electron-donating (**1b−1d**) and electron-withdrawing groups (**1e−1h**) at the para position on the aryl rings, although the latter showed lower efficiency. Typically functional groups,

Table 2. Cu-Catalyzed Oxidative Trifluoromethylation of 1,3,4-Oxadiazole Derivatives with CF_3SiMe_3 Under Air[a]



[a]Reaction conditions: **1** (0.3 mmol), CF_3SiMe_3 (1.2 mmol), $Cu(OAc)_2$ (40 mmol %), 1,10-phenanthroline (40 mmol %), *tert*-BuONa (0.33 mmol), NaOAc (0.9 mmol), and 4 Å MS (90 mg) in DCE (3.0 mL) at 80 °C for 6 h under air in a sealed tube, isolated yield. [b]Byproducts unidentified.

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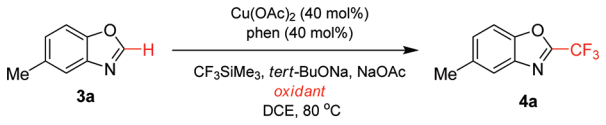
Table 3. Oxidant Optimization[a]



entry	oxidant (3.0 equiv)	yield (%)[b]
1[c]	air	28
2	di-*tert*-butyl peroxide	78 (72)[d]
3	Ag_2CO_3	43
4	$K_2S_2O_8$	27
5	DDQ	/
6	BQ	39

[a]Reaction conditions: **3a** (0.2 mmol), CF_3SiMe_3 (0.8 mmol), $Cu(OAc)_2$ (40 mmol %), 1,10-phenanthroline (40 mmol %), *tert*-BuONa (0.22 mmol), NaOAc (0.6 mmol), and 4 Å MS (60 mg) in DCE (2.0 mL) at 80 °C for 6 h under N_2 in a sealed tube. [b]Yield was determined by ^{19}F NMR spectroscopy using an internal standard. [c]Reaction was conducted under air. [d]Isolated yield in the parentheses.

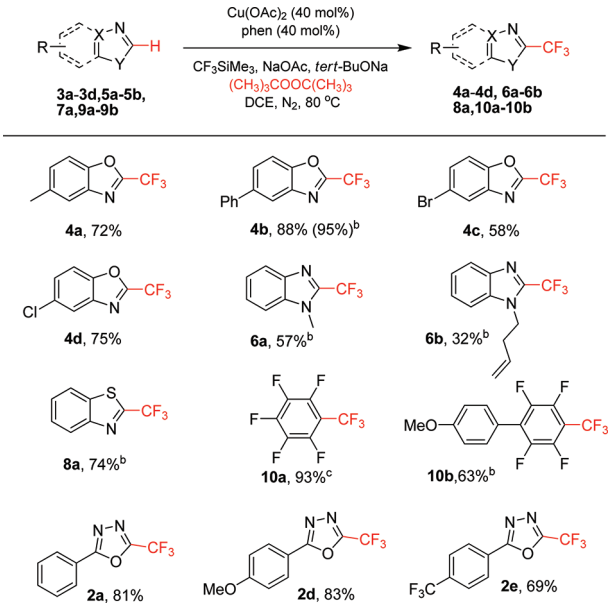
such as nitro and ester, were tolerated under the present reaction conditions (**1f** and **1g**).

Oxidative Trifluoromethylation of 1,3-Azoles and Perfluoroarenes. Encouraged by the results obtained with 1,3,4-oxadiazole, we proceeded to employ this oxidative trifluoromethylation protocol to other heteroarenes, such as 1,3-azoles, with similar acidic C−H bonds. Oxidative trifluoromethylation of 5-methylbenzo[*d*]oxazole (**3a**) under the same reaction conditions as those shown in Table 2 was sluggish, and the desired product **4a** was obtained in low yield (Table 3, entry 1). The reaction efficiency was significantly improved when di-*tert*-butyl peroxide was used as the oxidant instead of air (entry 2), while other organic and inorganic oxidants were less effective for this transformation (entries 3−6).

Under the modified reaction conditions, the oxidative trifluoromethylation scope of 1,3-azoles and perfluoroarenes was shown in Table 4. Benzo[*d*]oxazoles bearing various substituents underwent trifluoromethylation smoothly to give the corresponding trifluoromethylated benzo[*d*]oxazoles (**4a**−**4d**) in moderate to good yields. Functional groups, such as chloro and bromo, were compatible within the oxidative system, providing a complementary platform for further transformation. Benzo[*d*]imidazole and benzo[*d*]thiazole were also reactive, providing the corresponding trifluoromethylated products in moderate yields (**6a** and **6b**, **8a**). The trifluoromethylation of benzo[*d*]imidazole bearing a terminal alkene also worked well under the standard reaction condition, though the conversion was not complete and the compound **6b** was obtained in a low yield. Furthermore, electron-deficient pentafluorobenzene was highly reactive under these reaction conditions to afford octafluorotoluene (**10a**) in excellent yield. The efficient formation of $C_6F_5-CF_3$ bond between the highly electron-deficient pentafluorobenzene and the strongly electron-withdrawing CF_3 group in the presence of copper catalyst might provide a promising model for functionalizations of electron-deficient arenes. While the oxidative trifluoromethylation of 2,3,5,6-tetrafluoro-4′-methoxybiphenyl showed lower efficiency under the same reaction conditions to give product (**10b**) in moderate yield. This result showed that the pK_a of the C−H bonds has direct effect on the efficiency of the oxidative trifluoromethylation. In addition, di-*tert*-butyl peroxide also worked well as the oxidant for a variety of 1,3,4-oxadiazoles (**2a**, **2d**, and **2e**).

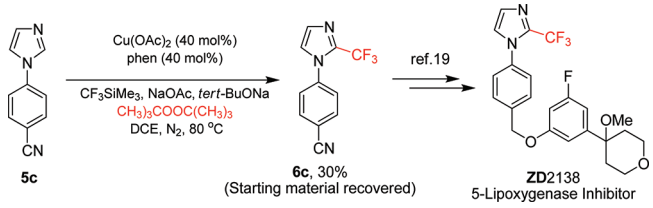
It is noteworthy that the oxidative trifluoromethylation of imidazole **5c** occurred under the same reaction conditions as those shown in Table 4 to afford compound **6c** selectively in moderate yield. Trifluoromethylated imidazole **6c** is an important intermediate for the synthesis of the potent 5-lipoxygense inhibitor ZD2138 (Scheme 2).[19]

Table 4. Cu-Catalyzed Oxidative Trifluoromethylation of Heteroarenes and Arenes with Di-*tert*-butyl Peroxide[a]



[a]Reaction conditions: **3** (0.3 mmol), CF_3SiMe_3 (1.2 mmol), $Cu(OAc)_2$ (40 mmol %), 1,10-phenanthroline (40 mmol %), *tert*-BuONa (0.33 mmol), NaOAc (0.9 mmol), di-*tert*-butyl peroxide (0.9 mmol), and 4 Å MS (90 mg) in DCE (3.0 mL) at 80 °C for 6 h under N_2 in a sealed tube, isolated yield. [b]Some starting material was recovered. [c]Yield was determined by ^{19}F NMR spectroscopy using an internal standard.

Scheme 2



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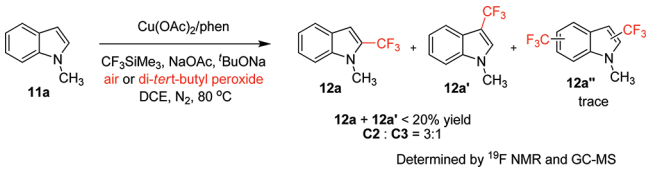
Oxidative Trifluoromethylation of Indoles. We had also attempted to apply these optimized oxidative trifluoromethylation reaction conditions to electron-rich indoles, because the indole framework is a privileged core structure in biological and medicinal chemistry and its trifluoromethylated derivatives have potential pharmaceutical applications.[20] Initially, *N*-methyl indole (**11a**) was chosen as the model substrate conducted under the standard reaction conditions (Tables 2 and 4). However, the expected products **12a** and **12a′** were observed in less than 20% yield under these optimized conditions, and the regioselectivity (C2/C3) was also not good (Scheme 3). A trace amount of side-product bearing CF_3 group

Scheme 3

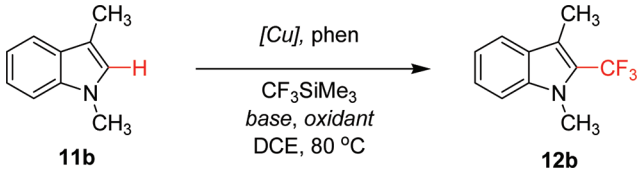


on the fused aryl group of indole was also detected by GC-MS, implying a radical process might be involved.[20g]

We speculated that the reaction processes of indoles and azoles might be different on the basis of the above experimental results. Thus, further optimization studies were performed to improve the efficiency of the oxidative trifluoromethylation of indoles. To simplify the regioselectivity problem, *N*-methyl-3-methylindole (**11b**) was chosen as a model substrate. The reaction conditions had been optimized with respect to bases, oxidants, and copper catalysts which played important roles in oxidative trifluoromethylation based on the aforementioned experimental results (Tables 1 and 3). As shown in Table 5, KF was chosen as the proper base for the oxidative trifluoromethylation of indoles (Table 5, entries 1−5). A screening of oxidants revealed that Ag_2CO_3 was the best one (entries 5−9). When $PhI(OAc)_2$ was used as oxidant, the desired product **12b** was obtained in almost identical yield accompanied by the side-product $PhCF_3$ derived from $PhI(OAc)_2$, which complicated purification (entry 8). Further screening of copper sources showed that **11b** was completely converted when $Cu(OH)_2$ was used as copper source instead of $Cu(OAc)_2$ (entries 10−14). However, the side products derived from the further trifluoromethylation of the fused aryl group of indole were observed (detected by ^{19}F NMR and GC-MS of reaction mixture). The formation of side products could be suppressed to a minimal extent by reducing the loading of $Cu(OH)_2$ catalyst to 10 mol %, and the yield of the desired product **12b** was improved to 93% (entries 14−16). Furthermore, the control experiments demonstrated that both copper and 1,10-phenanthroline were essential for the oxidative trifluoromethylation of indole (entry 17).

Under the new optimum reaction conditions (entry 16 of Table 5), a series of 3-subsituted indoles were successfully converted to the corresponding 2-trifluoromethyl indoles in good yields (Table 6). Indoles substituted with an N-protected group (such as methyl, ethyl, phenyl, or benzyl) were all amenable to the reaction conditions (**12b−12e**). A variety of functional groups on C5 position of indole, such as Cl, Br, and CO_2Me, were also tolerated (**12f−12h**). However, the oxidative trifluoromethylation was substantially affected by the electron density of the pyrrole ring. For example, only a trace amount of product was observed in the case of *N*-tosyl indole most likely because of the electron-withdrawing

Table 5. Optimization of Copper-Catalyzed Oxidative Trifluoromethylation of Indoles[a]



entry	copper (mmol %)	base (equiv)	oxidant (equiv)	yield[b] (%)
1	$Cu(OAc)_2$ (40)	*tert*-BuONa (1.1) + NaOAc (3.0)	air	15
2	$Cu(OAc)_2$ (40)	NaOAc (3.0)	air	12
3	$Cu(OAc)_2$ (40)	CsF (3.0)	air	20
4	$Cu(OAc)_2$ (40)	AgF (3.0)	air	14
5	$Cu(OAc)_2$ (40)	KF (3.0)	air	24
6	$Cu(OAc)_2$ (40)	KF (3.0)	di-*tert*-butyl peroxide (2.0)	13
7	$Cu(OAc)_2$ (40)	KF (3.0)	BQ (2.0)	trace
8	$Cu(OAc)_2$ (40)	KF (3.0)	$PhI(OAc)_2$ (2.0)	54
9	$Cu(OAc)_2$ (40)	KF (3.0)	Ag_2CO_3 (2.0)	53
10	CuI (40)	KF (3.0)	Ag_2CO_3 (2.0)	trace
11	CuOAc (40)	KF (3.0)	Ag_2CO_3 (2.0)	45
12	$CuCl_2$ (40)	KF (3.0)	Ag_2CO_3 (2.0)	6
13	$Cu(OTf)_2$ (40)	KF (3.0)	Ag_2CO_3 (2.0)	19
14	$Cu(OH)_2$ (40)	KF (3.0)	Ag_2CO_3 (2.0)	66
15	$Cu(OH)_2$ (20)	KF (3.0)	Ag_2CO_3 (2.0)	76
16	$Cu(OH)_2$ (10)	KF (3.0)	Ag_2CO_3 (2.0)	93 (87)[c]
17[d]	/	KF (3.0)	Ag_2CO_3 (2.0)	trace

[a]Reaction conditions: **11b** (0.2 mmol), CF_3SiMe_3 (0.6 mmol), 1,10-phenanthroline (the same equivalent with copper catalyst) in DCE (2.0 mL) at 80 °C for 12 h under N_2 in a sealed tube. [b]Yield was determined by ^{19}F NMR spectroscopy using an internal standard. [c]Isolated yield in the parentheses. [d]In the absence of $Cu(OH)_2$ and 1,10-phenanthroline.

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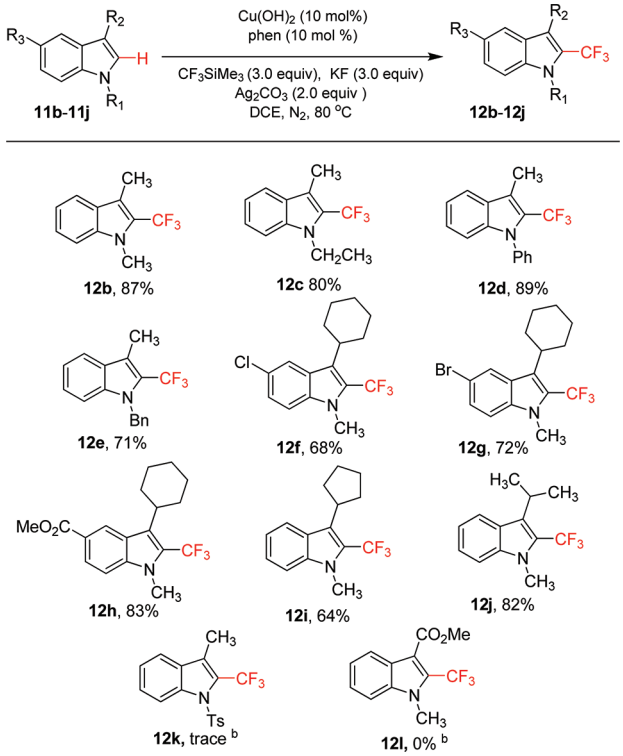
Table 6. Cu-Catalyzed Oxidative Trifluoromethylation of Indoles[a]

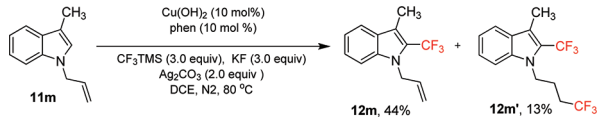


[a]Reaction conditions: **11** (0.4 mmol), CF_3SiMe_3 (1.2 mmol), $Cu(OH)_2$ (10 mmol %), 1,10-phenanthroline (10 mmol %), KF (1.2 mmol), Ag_2CO_3 (0.8 mmol) in DCE (3.0 mL) at 80 °C for 12 h under N_2 in a sealed tube, isolated yield. [b]Determined by ^{19}F NMR spectroscopy.

protection group (**12k**). Indole bearing the CO_2Me group on C3 position was also totally unreactive (**12l**).

Notably, in the case of *N*-allyl-3-methylindole (**11m**), the desired product **12m** was obtained in 44% yield, together with the further trifluoromethylation of the terminal olefin product **12m′** in 13% yield (Scheme 4). This result and the observation

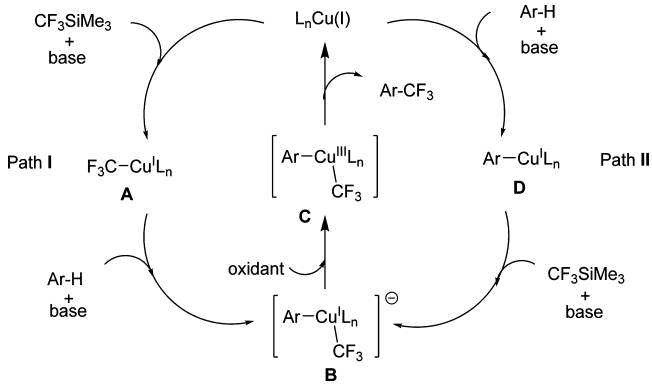
Scheme 4



of trifluoromethylation of fused aryl group of indole indicated that trifluoromethyl radical (CF_3·) might be involved in the oxidative trifluoromethylation of indoles.

Mechanistic Investigations. A plausible mechanism for the copper-catalyzed oxidative trifluoromethylation of heteroarenes and polyfluoroarenes is proposed in Scheme 5. First, reduction[16n] or disproportionation[21] of a Cu(II) catalyst into a Cu(I) species, followed by reaction with trifluoromethylsilicate generated in situ would afford the $CF_3Cu^IL_n$ species **A** as the key intermediate.[11,12] Subsequent transmetalation with activation of Ar–H would generate the (aryl)$Cu^I(CF_3)$ species **B**, which might be oxidized to the corresponding (aryl)$Cu^{III}(CF_3)$ intermediate **C**.[21] Finally, reductive elimination of the (aryl)-$Cu^{III}(CF_3)$ intermediate **C** would give the expected product and regenerate the catalyst to complete the catalytic cycle

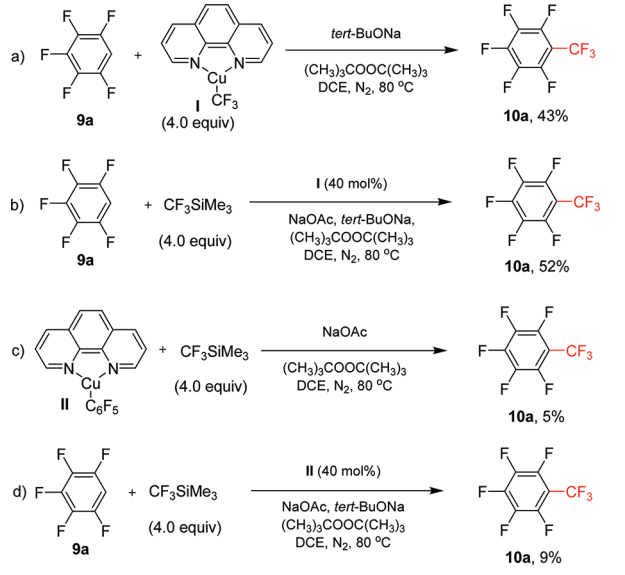
Scheme 5. Plausible Mechanism



(Scheme 5, path **I**). Alternatively, a catalytic cycle involving the initial generation of the arylcopper complex **D**, which was generally suggested as the key intermediate in the Cu-mediated C–H functionalization of heteroaromatic compounds under basic conditions,[16] might be possible. The transmetalation of arylcopper complex **D** with trifluoromethylsilicate generated in situ would lead to the formation of (aryl)$Cu^I(CF_3)$ species **B**, which subsequently would deliver the cross-coupling product (Scheme 5, path **II**).

To further probe the reaction mechanism illustrated in Scheme 5, preliminary mechanistic studies have been performed. Considering the preparation of pentafluorophenylcopper–phenanthroline complex (phen)CuC_6F_5 has been reported by Daugulis,[16a] we chose pentafluorobenzene (**9a**) as the model substrate to conduct these experiments. First, the trifluoromethylcopper–phenanthroline complex (phen)$CuCF_3$ (**I**)[11k] and pentafluorophenylcopper–phenanthroline complex (phen)CuC_6F_5 (**II**)[16a] were prepared according to the literatures. With these two complexes in hand, we then conducted several stoichiometric and catalytic oxidative trifluoromethylation reactions. As shown in Scheme 6, the

Scheme 6



reactions of **9a** with 4.0 equivalents of isolated (phen)$CuCF_3$ (**I**) gave the desired cross-coupling product **10a** in 43% yield (Scheme 6a). Furthermore, the oxidative trifluoromethylation

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of **9a** with 4.0 equiv of CF_3SiMe_3 in the presence of catalytic amount of (phen)$CuCF_3$ (**I**) (40 mol %) also afforded compound **10a** in 52% yield (Scheme 6b). In the sharp contrast, only trace **10a** was detected in the reaction of isolated (phen)CuC_6F_5 (**II**) with 4.0 equiv of CF_3SiMe_3 (Scheme 6c). The reaction of **9a** with CF_3SiMe_3 in the presence of a catalytic amount of (phen)CuC_6F_5 (**II**) was also sluggish (Scheme 6d). These results indicated that the catalytic cycle via path **I** involving the $CF_3Cu^IL_n$ species is more reasonable. It was noteworthy that the efficiency of the oxidative trifluoromethylation of pentafluorobenzene under the catalysis of isolated (phen)$CuCF_3$ (**I**) (Scheme 6b) was lower than that of the catalytic transformation in the presence of catalytic amount of $Cu(OAc)_2$/phenanthroline (Table 4). This was due to the (phen)$CuCF_3$ (**I**) decomposition in the presence of base and oxidant ((phen)$CuCF_3$ (**I**) underwent decomposition in the presence of NaOAc, *tert*-BuONa, and di-*tert*-butyl peroxide, for more details, see Supporting Information).

CONCLUSION

An operationally simple, straightforward, and efficient method for copper-catalyzed oxidative trifluoromethylations of heteroarenes and highly electron-deficient arenes with CF_3SiMe_3 has been developed. Using this method, a wide range of aromatics, including 1,3,4-oxadiazoles, benzo[*d*]xazoles, benzo[*d*]thiazole, benzo[*d*]imidazoles, indoles, and electron-deficient perfluoroarenes, were converted into their corresponding trifluoromethylated derivatives in moderate to excellent yields. Importantly, most common functionalities, such as ester, nitro, nitrile, and bromo, are well-tolerated. Preliminary mechanistic investigations indicated that the catalytic cycle occurs via the generation a $CF_3Cu^IL_n$ complex as the key intermediate, instead of the generally accepted $ArCu^IL_n$ complex.

ASSOCIATED CONTENT

Supporting Information

Full experimental details and characterization data. This material is available free of charge via the Internet at http://pubs.acs.org.

AUTHOR INFORMATION

Corresponding Author

flq@mail.sioc.ac.cn

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