JACS
JOURNAL OF THE AMERICAN CHEMICAL SOCIETY

Communication

pubs.acs.org/JACS

Distinct Mechanism of Oxidative Trifluoromethylation with a Well-Defined Cu(II) Fluoride Promoter: Hidden Catalysis

Noel Nebra and Vladimir V. Grushin*

Institute of Chemical Research of Catalonia (ICIQ), 43007 Tarragona, Spain

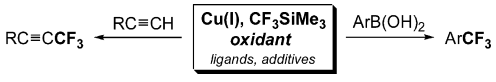
Supporting Information

ABSTRACT: The fluoride $[(bpy)CuF_2(H_2O)]\cdot 2H_2O$ (**1**) reacts with CF_3SiMe_3 and $PhB(OH)_2$ in DMF at rt to give $PhCF_3$ in >95% yield within 15 min. Although **1** is a Cu(II) complex, this reaction occurs only in air; no Ph-CF_3 coupling takes place under anaerobic conditions. A distinct mechanism is operational in this transformation. First, **1** is trifluoromethylated with $TMSCF_3$ to give "$[(bpy)Cu(CF_3)_2]$" that spontaneously disproportionates to two Cu(III) ($[Cu(CF_3)_4]^-$ and $[(bpy)Cu(CF_3)_3]$) and two Cu(I) ($[(bpy)Cu(CF_3)]$ and $[Cu(CF_3)_2]^-$) complexes. In contrast with the Chan–Evans–Lam reaction, where the Cu(III) products of the Cu(II) disproprotionation effect the coupling, those formed in the **1**-$TMSCF_3$ system, $[Cu(CF_3)_4]^-$ and $[(bpy)Cu(CF_3)_3]$, are stable and unreactive, remaining dead-end spectators throughout the coupling process. Consequently, the trifluoromethylation of $PhB(OH)_2$ with **1**-CF_3SiMe_3 does not and cannot occur in the absence of O_2. Only by air oxidation of the Cu(I) disproportionation product, $[(bpy)Cu(CF_3)]$ in equilibrium with $[Cu(CF_3)_2]^-$, is the reactive species generated, serving as a catalyst for the Ph-CF_3 bond formation even if **1** is used in stoichiometric quantities.

In 2010, Chu and Qing reported their pioneering findings of Cu-promoted/catalyzed oxidative trifluoromethylation of terminal acetylenes[1] and arylboronic acids[2] (Scheme 1). Publications of alternative/improved protocols for both transformations from Qing's group[3] and others[4,5] as well as a computational study of the alkyne trifluoromethylation[6] quickly followed. These C-CF_3 bond forming reactions contribute significantly to trifluoromethylation methods[7] for medicinal chemistry, agrochemical, and materials science research. Considering the high synthetic value of these transformations, it is important to understand their mechanism that is "still unclear and remains to be elucidated".[3c]

Unless an electrophilic ("CF_3^+") source is employed,[4b−d,g,i,5] these seemingly Chan–Evans–Lam (CEL)-type[8,9] coupling reactions require an oxidant to occur. The role of the oxidant such as Ag(I),[1,3] pure O_2,[4a] or air[4h] is to convert the conventionally used for the reaction *nucleophilic* Cu(I) species that are *unreactive* toward arylboron and terminal alkyne nucleophiles to a higher oxidation state, *reactive electrophilic* Cu complexes.

Scheme 1. Oxidative Trifluoromethylation of Arylboronic Acids and 1-Alkynes



In theory, if the oxidative trifluoromethylation was mechanistically[10,11] similar to the CEL reaction, the C-CF_3 coupling with stoichiometric Cu(II) could occur to 50% conversion in the absence of an oxidant. In an elegant mechanistic study, Stahl et al.[10] have demonstrated that *p*-$TolB(OH)_2$ reacts with MeOH in the presence of 1 equiv of Cu(II) to give *p*-TolOMe in 50% yield in an inert atmosphere. The disproportionation of the added Cu(II) promoter leads to 50% of inactive Cu(I) and 50% of active Cu(III) that effects the methoxylation. On introduction of O_2, the Cu(I) is oxidized to the Cu(III), thereby raising the yield of *p*-TolOMe to quantitative.[10]

Is the same mechanism operational in the oxidative trifluoromethylation reactions with nucleophilic CF_3 reagents (Scheme 1)? In other words, can the C-CF_3 bond formation occur with stoichiometric Cu(II) in the absence of an oxidant? Cu(II) promoters have been successfully used for the Ar-CF_3 coupling of arylboronic acids and boronate esters with nucleophilic CF_3 reagents CF_3SiMe_3 ($TMSCF_3$)[4a] and $K[(CF_3)B(OMe)_3]$.[4e] All of these reactions, however, were performed under O_2 as an external oxidant. Whether or not $ArCF_3$ would be still produced, at least in some quantities, under identical conditions with a Cu(II) promoter but in the absence of O_2, remains unknown.

Herein we report that in contrast to the CEL reaction, oxidative trifluoromethylation of arylboronic acids in the presence of electrophilic Cu(II) may not occur without an oxidant (O_2). We demonstrate that a Cu(II)-promoted oxidative trifluoromethylation reaction is governed by a peculiar mechanism that is distinct from that of the classical CEL coupling. This unexpected mechanism involves "hidden catalysis" even if the Cu(II) promoter is used in equimolar quantities.

Given the high affinity of silicon and boron for fluorine, we originally selected anhydrous CuF_2 as a model Cu(II) promoter for the coupling of $PhB(OH)_2$ with $TMSCF_3$. Agitating a 1:1:1 mixture of CuF_2, $PhB(OH)_2$, and $TMSCF_3$ in a variety of dry solvents at ambient temperature under argon or in air for 12 h did not produce $PhCF_3$ in ^{19}F NMR-detectable quantities.[12] Considering the exceptionally poor solubility of CuF_2, we then turned our attention to soluble Cu(II) fluorides. Well-defined, structurally characterized fluoro complexes of Cu(II) are rare. For our studies, we selected $[(bpy)CuF_2(H_2O)]\cdot 2H_2O$ (**1**; bpy = 2,2′-bipyridyl) and $[(phen)CuF_2(H_2O)]\cdot 2H_2O$ (**2**; phen = 1,10-phenanthroline).[13,14] On addition of $TMSCF_3$ (10 equiv) to **1** or **2** in dry DMF, the pale-

Received: October 15, 2014

   dx.doi.org/10.1021/ja5103508 | J. Am. Chem. Soc. XXXX, XXX, XXX−XXX

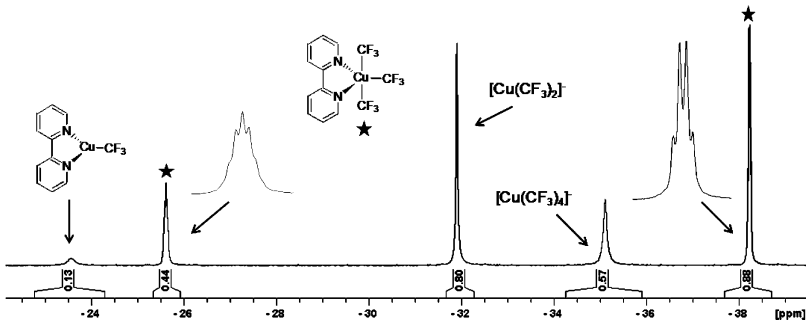


Figure 1. $CuCF_3$ region of the ^{19}F NMR spectrum of the reaction mixture obtained upon treatment of **1** with $TMSCF_3$ (20 equiv) in DMF under argon with integral intensity of the peak from 4,4′-difluorobiphenyl as an internal standard (−118.0 ppm) set at 2.00. See Figure S1 for the full spectrum.

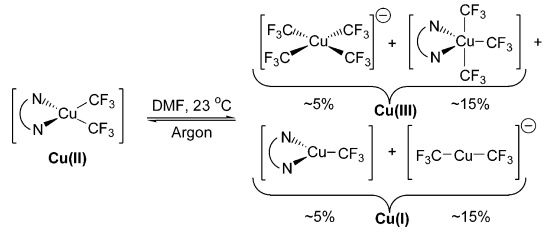
blue fluorides dissolved within 1 min. Adding $PhB(OH)_2$ (1 equiv) to the resultant dark orange-red solution in air prompted the formation of $PhCF_3$ in a fast reaction that was complete within 15−30 min at 23 °C. In the initial runs, the yield of $PhCF_3$ in the reaction with **1** was higher (75%) than with **2** (25%). Therefore, **1** was chosen for further studies. After optimization (see the Supporting Information), the reaction of **1** (1 equiv) with $TMSCF_3$ (10 equiv) and $PhB(OH)_2$ (1 equiv) in DMF in air furnished $PhCF_3$ quantitatively (>95%). The need to use a large excess of $TMSCF_3$ for the reaction was dictated by the presence in **1** and **2** of one coordinated and two H-bonded H_2O molecules that hydrolyze $TMSCF_3$ (see below).

The reaction of **1** with $TMSCF_3$ and $PhB(OH)_2$ was then repeated under identical conditions but under argon, i.e., *in the absence of* O_2. Although visual signs of the reaction (quick dissolution of **1** and color change) were the same, no $PhCF_3$ was produced. The lack of Ph-CF_3 bond formation under anaerobic conditions using a Cu(II) complex suggested that the trifluoromethylation mechanism in the **1**-$TMSCF_3$-O_2 system might be different from that of the CEL coupling (see above). We therefore undertook a more detailed study of the reaction of **1** with $TMSCF_3$ in the absence and in the presence of O_2.

The dark orange-red solution produced on addition of $TMSCF_3$ (20 equiv) to **1** in dry DMF under rigorously O_2-free conditions (argon glovebox) was analyzed by ^{19}F NMR in the presence of an internal standard (4,4′-difluorobiphenyl). The spectrum (Figure S1) indicated full transfer of both F atoms from Cu to the $SiMe_3$ unit to give TMSF quantitatively (2 equiv). Fluoroform (CHF_3) was also produced (6 equiv) as a result of hydrolysis of 6 equiv of $TMSCF_3$ with the three H_2O molecules present in **1** (eq 1). In excellent agreement of the mass balance with the stoichiometry, 12 of the originally used 20 equiv of $TMSCF_3$ remained intact.

$$\underset{(\mathbf{1},\ \textit{1 equiv})}{[(bpy)CuF_2(H_2O)_3]} + \underset{(\textit{20 equiv})}{TMSCF_3} \xrightarrow[\text{argon}]{\text{DMF, 23 °C}} \text{"}[(bpy)Cu(CF_3)_2]\text{"} + \underset{(\textit{2 equiv})}{TMSF} + \underset{(\textit{6 equiv})}{CHF_3} + (TMS)_2O + \underset{(\textit{12 equiv})}{TMSCF_3} \quad (1)$$

The experimentally demonstrated stoichiometry (eq 1) suggested full conversion of **1** to "$[(bpy)Cu(CF_3)_2]$",[15] a paramagnetic Cu(II) species that should be unobservable by NMR. Unexpectedly, however, a number of resonances could be clearly seen in the characteristic "$CuCF_3$" region of the ^{19}F NMR spectrum (−20 to −40 ppm), pointing to the presence of diamagnetic Cu complexes bearing a CF_3 ligand (Figure 1). Examination of these signals indicated that two $CF_3Cu(I)$ and two $CF_3Cu(III)$ species were produced. The Cu(III) complexes were $[Cu(CF_3)_4]^-$ resonating as a singlet at −35.1 ppm[16] and $[(bpy)Cu(CF_3)_3]$[17] displaying a quartet at −38.2 ppm ($J_{F\text{-}F}$ = 8.9 Hz) and a septet at −25.6 ppm with the same coupling constant, in a 2:1 integral ratio. These assignments were confirmed by spiking experiments with authentic samples. The other two resonances, a broadened singlet at −23.6 ppm and a singlet at −31.9 ppm were assigned to Cu(I) complexes $[(bpy)Cu(CF_3)]$ and $[Cu(CF_3)_2]^-$, respectively, on the basis of the reported data for the analogous phen complex[18] and a structurally characterized salt of $[Cu(CF_3)_2]^-$.[19] These two Cu(I) complexes most likely equilibrate, similar to the phen[18] and NHC[19] systems. The yields of $[Cu(CF_3)_4]^-$ (5%), $[(bpy)Cu(CF_3)_3]$ (15%), $[(bpy)Cu(CF_3)]$ (5%), and $[Cu(CF_3)_2]^-$ (15%) were quantified using the internal standard. Therefore, ∼40% of the $CF_3Cu(II)$ species produced in the reaction of **1** with $TMSCF_3$ disproportionated to Cu(I) and Cu(III) (eq 2).[20] The Cu(II), Cu(I), and Cu(III) equilibrated within minutes, after which no evolution of the ^{19}F NMR spectral pattern (Figure 1) was observed for at least 4 h.



(2)

Two of the four species formed in the disproportionation, $[Cu(CF_3)_4]^-$ and $[Cu(CF_3)_2]^-$, are anionic and hence must have countercations, such as $[(bpy)_2Cu]^{2+}$, $[(bpy)_3Cu]^{2+}$, or $[(bpy)_2Cu(CF_3)]^+$. With the latter two, the disproportionation equations (eqs 3 and 4) can be balanced, the stoichiometry being in full accord with the experimental data, i.e., $[Cu(CF_3)_2]^-$:$[(bpy)Cu(CF_3)]$:$[Cu(CF_3)_4]^-$:$[(bpy)Cu(CF_3)_3]$ = 3:1:1:3. In contrast, the equation with $[(bpy)_2Cu]^{2+}$ as the counterion is not balanceable. Well-known and stable $[(bpy)_3Cu]^{2+}$ (eq 3) is more likely the countercation than $[(bpy)_2Cu(CF_3)]^+$ (eq 4).[15]

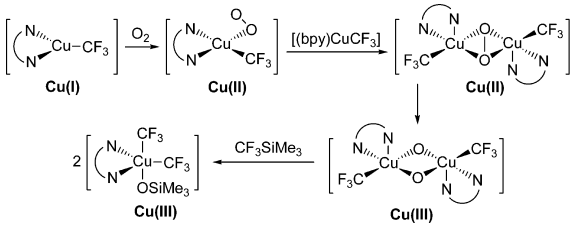
$$20[(bpy)Cu(CF_3)_2] = 3[(bpy)_3Cu]^{2+}([Cu(CF_3)_2]^-)_2 + 2[(bpy)Cu(CF_3)] + [(bpy)_3Cu]^{2+}([Cu(CF_3)_4]^-)_2 + 6[(bpy)Cu(CF_3)_3] \quad (3)$$

$$12[(bpy)Cu(CF_3)_2] = 3[(bpy)_2Cu(CF_3)]^+[Cu(CF_3)_2]^- + [(bpy)Cu(CF_3)] + [(bpy)_2Cu(CF_3)]^+[Cu(CF_3)_4]^- + 3[(bpy)Cu(CF_3)_3] \quad (4)$$

Adding $PhB(OH)_2$ (1 equiv) to the equilibrated system (eqs 2 and 3) under argon produced no reaction, indicating that the Cu(III) species from the disproportionation are coupling incompetent. Opening the resultant solution to air, however, triggered the formation of $PhCF_3$ in ∼40% yield within 10 min. The coupling was obviously effected by the products of oxidation of the Cu(I) complexes emerged from the disproportionation.

dx.doi.org/10.1021/ja5103508 | J. Am. Chem. Soc. XXXX, XXX, XXX−XXX

Scheme 2. Air Oxidation of [(bpy)Cu(CF_3)] in the Presence of $TMSCF_3$ Leading to [(bpy)Cu(CF_3)$_2$(OTMS)]



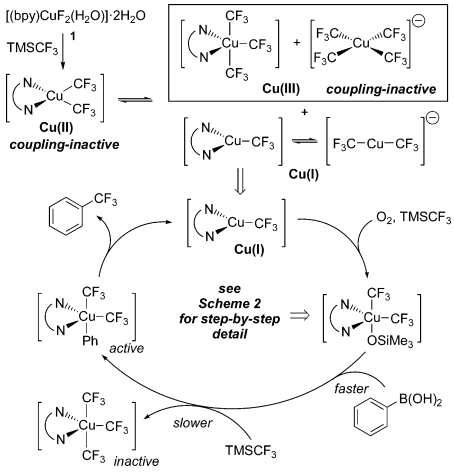
The reaction of **1** with $TMSCF_3$ (20 equiv) in DMF was then repeated in air. Just as under anaerobic conditions, blue **1** quickly dissolved to give a dark-orange solution. Again, TMSF (2 equiv) and CHF_3 (6 equiv) were quantitatively produced, with 12 equiv of $TMSCF_3$ remaining intact (eq 1 and Figure S3). Both previously observed Cu(III) complexes, [(bpy)Cu(CF_3)$_3$] and [Cu(CF_3)$_4$]$^-$, were also formed. The signals from the Cu(I) species [(bpy)Cu(CF_3)] and [Cu(CF_3)$_2$]$^-$, however, were absent. Instead, the spectrum exhibited two new resonances, broadened quartets of equal intensity at −27.1 and −32.2 ppm with the same coupling constant $J_{F\text{-}F}$ = 11.6 Hz (Figure S4). A new singlet resonance at −0.55 ppm was concomitantly observed in the ^{1}H NMR spectrum of the reaction solution, suggesting a TMSO-Cu complex.[21] It was reasoned that the ^{19}F NMR quartets and the −0.55 ppm ^{1}H NMR singlet were probably from the same species, [(bpy)Cu(CF_3)$_2$(OTMS)], with one CF_3 and OTMS in the apical positions. Integration of the singlet at −0.55 ppm against the aromatic protons of the internal standard provided strong support to this proposal, as the yield of [(bpy)Cu(CF_3)$_2$(OTMS)] determined independently from the ^{19}F NMR and ^{1}H NMR data was the same, ∼10−15%. Scheme 2 accounts for the formation of the [(bpy)Cu(CF_3)$_2$(OTMS)], lending additional support from the mechanism[6] of oxidation of [(phen)Cu(CF_3)] with O_2.

Once formed, the Cu-OTMS complex was slowly (hours) transforming to [Cu(CF_3)$_4$]$^-$ and [(bpy)Cu(CF_3)$_3$]. The latter was predominantly produced, suggesting that [(bpy)Cu(CF_3)$_2$(OTMS)] reacted with $TMSCF_3$ to give [(bpy)Cu(CF_3)$_3$] and $(TMS)_2O$. After 30 h, the overall yield of [Cu(CF_3)$_4$]$^-$ and [(bpy)Cu(CF_3)$_3$] was ∼90%. Adding $PhB(OH)_2$ to the sample at that point resulted in no reaction, confirming, again, the incapability of [Cu(CF_3)$_4$]$^-$ and [(bpy)Cu(CF_3)$_3$] to effect the coupling.

In another experiment, $PhB(OH)_2$ (1 equiv) was added to the freshly generated [(bpy)Cu(CF_3)$_2$(OTMS)], and the tube was sealed in air. Shaking the contents for ∼15 min resulted in full disappearance of the OTMS complex and the formation of $PhCF_3$, albeit in only 80% yield (^{19}F NMR). Both [(bpy)Cu(CF_3)] and [Cu(CF_3)$_2$]$^-$ were also observed. The formation of the Cu(I) species was evidently due to full consumption of the O_2 present in the sealed tube as a limiting reagent. Replenishing the supply of O_2 to the reaction by re-opening the tube to air resulted in quantitative formation of $PhCF_3$ and disappearance of the Cu(I) complexes.

The current study uncovers the mechanism of the oxidative trifluoromethylation reaction (Scheme 3). First, **1** reacts with $TMSCF_3$ to give rise to "[(bpy)Cu(CF_3)$_2$]",[15] a Cu(II) complex that undergoes spontaneous facile disproportionation[22] to Cu(I) ([Cu(CF_3)$_2$]$^-$ and [(bpy)Cu(CF_3)]) and Cu(III) ([Cu(CF_3)$_4$]$^-$ and [(bpy)Cu(CF_3)$_3$]) at ∼40% conversion. None of the Cu(I), Cu(II), and Cu(III) species in the resultant system is reactive toward $PhB(OH)_2$ under anaerobic conditions. Both of the Cu(III) complexes produced are stable and unreactive, remaining

Scheme 3. Mechanism of Oxidative Trifluoromethylation of $PhB(OH)_2$ with 1-$TMSCF_3$



spectators throughout the process. It is the Cu(I) products of the disproportionation, [Cu(CF_3)$_2$]$^-$ in equilibrium[18] with [(bpy)-Cu(CF_3)], that effect the coupling. The more reactive bpy-ligated species enters the catalytic loop to undergo facile oxidation with O_2,[6] which initiates the formation of the key intermediate [(bpy)Cu(CF_3)$_2$(OTMS)] (Scheme 2). Two reaction pathways are available for [(bpy)Cu(CF_3)$_2$(OTMS)] (Scheme 3). One is the trifluoromethylation of the Cu-OTMS bond with $TMSCF_3$, leading to inactive [(bpy)Cu(CF_3)$_3$]. This unproductive pathway irreversibly pulls out the active species from the catalytic cycle. The other, luckily faster productive pathway involves transmetalation with $PhB(OH)_2$, followed by Ph-CF_3 reductive elimination from the resultant CF_3(Ph)Cu(III) species.[23] The thus regenerated [(bpy)Cu(CF_3)] then commences another catalytic turnover. As catalytically competent [(bpy)Cu(CF_3)] is consumed, productively or nonproductively, the disproportionation equilibrium is shifted toward the formation of more of the Cu(I) precursors to the active species and inactive Cu(III) complexes. In this way, the CF_3Cu(II) species produced in the reaction of **1** with $TMSCF_3$ serves as a reservoir of the productive Cu(I) and the "dead-end" Cu(III) in a 1:1 ratio. Therefore, the oxidative trifluoromethylation with **1**-$TMSCF_3$ is, mechanistically, catalytic in Cu even if **1** is used in stoichiometric quantities for the reaction.

In conclusion, **1**, a well-defined Cu(II) fluoride complex, is a highly efficient promoter for the high-yielding oxidative trifluoromethylation of $PhB(OH)_2$ with $TMSCF_3$ at rt in air. A distinct mechanism is operational in this transformation. Like in the classical CEL reaction, disproportionation of Cu(II) occurs first to give Cu(I) and Cu(III). In contrast, however, both of the Cu(III) species produced, [Cu(CF_3)$_4$]$^-$ and [(bpy)Cu(CF_3)$_3$], are unreactive toward $PhB(OH)_2$, remaining spectators throughout the process. Only through air oxidation of the Cu(I) products of the disproportionation ([(bpy)Cu(CF_3)] in equilibrium with [Cu(CF_3)$_2$]$^-$) does the reactive species emerge, serving as a *catalyst* for the coupling. Consequently, unlike the CEL reaction that can produce the desired product in 50% yield in the presence of stoichiometric Cu(II) under anaerobic conditions,[10] the trifluoromethylation with $TMSCF_3$ in the presence of **1**, also a Cu(II) complex, *cannot* occur in the absence of O_2. This key difference prompts us to arrive at the striking conclusion that, at least in some instances, Cu(I) rather than Cu(II) added catalysts/promoters can exhibit higher efficiency in oxidative trifluoromethylation reactions. The novel mechanistic insights

dx.doi.org/10.1021/ja5103508 | J. Am. Chem. Soc. XXXX, XXX, XXX−XXX

from the current work may find use in the development of new, more efficient catalysts and promoters for trifluoromethylation methods.[24]

■ ASSOCIATED CONTENT

Supporting Information

Experimental details and NMR spectra. This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

vgrushin@iciq.es

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We thank F. M. Miloserdov and A. Lishchynskyi for discussions and for valuable comments. This work was supported by the ICIQ Foundation and the Spanish Government (grant CTQ2011-25418). N.N. is thankful to ICIQ and Marie Curie Actions for the cofunded "ICIQ-IPMP" postdoctoral grant award 291787.

■ REFERENCES

(1) Chu, L.; Qing, F.-L. *J. Am. Chem. Soc.* **2010**, *132*, 7262.

(2) Chu, L.; Qing, F.-L. *Org. Lett.* **2010**, *12*, 5060.

(3) (a) Jiang, X.; Chu, L.; Qing, F.-L. *J. Org. Chem.* **2012**, *77*, 1251. (b) Zhang, K.; Qiu, X.-L.; Huang, Y.; Qing, F.-L. *Eur. J. Org. Chem.* **2012**, 58. (c) Chu, L.; Qing, F.-L. *Acc. Chem. Res.* **2014**, *47*, 1513.

(4) Boronic acids and boronate esters: (a) Senecal, T. D.; Parsons, A.; Buchwald, S. L. *J. Org. Chem.* **2011**, *76*, 1174. (b) Xu, J.; Luo, D.-F.; Xiao, B.; Liu, Z.-J.; Gong, T.-J.; Fu, Y.; Liu, L. *Chem. Commun.* **2011**, *47*, 4300. (c) Zhang, C.-P.; Cai, J.; Zhou, C.-B.; Wang, X.-P.; Zheng, X.; Guc, Y.-C.; Xiao, J.-C. *Chem. Commun.* **2011**, *47*, 9516. (d) Liu, T.; Shen, Q. *Org. Lett.* **2011**, *13*, 2342. (e) Khan, B. A.; Buba, A. E.; Gooßen, L. J. *Chem.—Eur. J.* **2012**, *18*, 1577. (f) Litvinas, N. D.; Fier, P. S.; Hartwig, J. F. *Angew. Chem., Int. Ed.* **2012**, *51*, 536. (g) Liu, T.; Shao, X.; Wu, Y.; Shen, Q. *Angew. Chem., Int. Ed.* **2012**, *51*, 540. (h) Novák, P.; Lishchynskyi, A.; Grushin, V. V. *Angew. Chem., Int. Ed.* **2012**, *51*, 7767. (i) Ye, Y.; Sanford, M. S. *J. Am. Chem. Soc.* **2012**, *134*, 9034. (j) Ye, Y.; Künzi, S. A.; Sanford, M. S. *Org. Lett.* **2012**, *14*, 4979. (k) Li, Y.; Wu, L.; Neumann, H.; Beller, M. *Chem. Commun.* **2013**, *49*, 2628. (l) Presset, M.; Oehlrich, D.; Rombouts, F.; Molander, G. A. *J. Org. Chem.* **2013**, *78*, 12837.

(5) Terminal acetylenes: (a) Luo, D.-F.; Xu, J.; Fu, Y.; Guo, Q.-X. *Tetrahedron Lett.* **2012**, *53*, 2769. (b) Weng, Z.; Li, H.; He, W.; Yao, L.-F.; Tan, J.; Chen, J.; Yuan, Y.; Huang, K.-W. *Tetrahedron* **2012**, *68*, 2527. (c) Wang, X.; Lin, J.; Zhang, C.; Xiao, J.; Zheng, X. *Chin. J. Chem.* **2013**, *31*, 915. (d) Serizawa, H.; Aikawa, K.; Mikami, K. *Chem.—Eur. J.* **2013**, *19*, 17692. (e) Tresse, C.; Guissart, C.; Schweizer, S.; Bouhoute, Y.; Chany, A.-C.; Goddard, M.-L.; Blanchard, N.; Evano, G. *Adv. Synth. Catal.* **2014**, *356*, 2051. (f) Dubbaka, S. R.; Nizalapur, S.; Atthunuri, A. R.; Salla, M.; Mathew, T. *Tetrahedron* **2014**, *70*, 2118. (g) Deng, X.; Lin, J.; Zheng, J.; Xiao, J. *Chin. J. Chem.* **2014**, *32*, 689.

(6) Jover, J.; Maseras, F. *Chem. Commun.* **2013**, *49*, 10486.

(7) For selected reviews, see: (a) Burton, D. J.; Yang, Z. Y. *Tetrahedron* **1992**, *48*, 189. (b) McClinton, M. A.; McClinton, D. A. *Tetrahedron* **1992**, *48*, 6555. (c) Schlosser, M. *Angew. Chem., Int. Ed.* **2006**, *45*, 5432. (d) Roy, S.; Gregg, B. T.; Gribble, G. W.; Le, V.-D.; Roy, S. *Tetrahedron* **2011**, *67*, 2161. (e) Qing, F.-L.; Zheng, F. *Synlett* **2011**, 1052. (f) Tomashenko, O. A.; Grushin, V. V. *Chem. Rev.* **2011**, *111*, 4475. (g) Jin, Z.; Hammond, G. B.; Xu, B. *Aldrichimica Acta* **2012**, *45*, 67. (h) Chen, P.; Liu, G. *Synthesis* **2013**, *45*, 2919. (i) Landelle, G.; Panossian, A.; Pazenok, S.; Vors, J.-P.; Leroux, F. R. *Beilstein J. Org. Chem.* **2013**, *9*, 2476.

(8) (a) Chan, D. M. T.; Monaco, K. L.; Wang, R. P.; Winters, M. P. *Tetrahedron Lett.* **1998**, *39*, 2933. (b) Evans, D. A.; Katz, J. L.; West, T. R. *Tetrahedron Lett.* **1998**, *39*, 2937. (c) Lam, P. Y. S.; Clark, C. G.; Saubern, S.; Adams, J.; Winters, M. P.; Chan, D. M. T.; Combs, A. *Tetrahedron Lett.* **1998**, *39*, 2941.

(9) For selected reviews, see: (a) Ley, S.; Thomas, A. W. *Angew. Chem., Int. Ed.* **2003**, *42*, 5400. (b) Beletskaya, I. P.; Cheprakov, A. V. *Coord. Chem. Rev.* **2004**, *248*, 2337. (c) Evano, G.; Blanchard, N.; Toumi, M. *Chem. Rev.* **2008**, *108*, 3054. (d) Monnier, F.; Taillefer, M. *Angew. Chem., Int. Ed.* **2009**, *48*, 6954. (e) Qiao, J. X.; Lam, P. Y. S. *Synthesis* **2011**, 829. (f) Allen, S. E.; Walvoord, R. R.; Padilla-Salinas, R.; Kozlowski, M. C. *Chem. Rev.* **2013**, *113*, 6234. (g) Casitas, A.; Ribas, X. *Chem. Sci.* **2013**, *4*, 2301.

(10) King, A. E.; Brunold, T. C.; Stahl, S. S. *J. Am. Chem. Soc.* **2009**, *131*, 5044.

(11) Wendlandt, A. E.; Suess, A. M.; Stahl, S. S. *Angew. Chem., Int. Ed.* **2011**, *50*, 11062.

(12) (a) Solvents explored: DMF, THF, DME, DCE, DME, NMP, MeCN, toluene, DMSO, and DMAC. After prolonged heating at 85 °C in DMSO or DMF, small quantities of $PhCF_3$ (~5%) were formed. (b) A mixture of 1-naphthylboronic acid pinacol ester (1 equiv) and $K^+[(CF_3)B(OMe)_3]^-$ (2 equiv) has been reported[4e] to react with CuF_2 in DMSO under O_2 at 80 °C to give 1-$C_{10}H_7CF_3$ (15%), 1-$C_{10}H_7OMe$ (37%), and 1,1′-binaphthyl (42%).

(13) (a) These complexes were originally prepared by Levason et al.[13b] by the reaction of $CuF_2{\cdot}xH_2O$ with bpy or phen in MeOH and subsequently structurally characterized by Hursthouse.[13c,d] (b) Gibbs, P. R.; Graves, P. R.; Gulliver, D. J.; Levason, W. *Inorg. Chim. Acta* **1980**, *45*, L207. (c) Emsley, J.; Arif, M.; Bates, P. A.; Hursthouse, M. B. *J. Crystallogr. Spectrosc. Res.* **1987**, *17*, 605. (d) Emsley, J.; Arif, M.; Bates, P. A.; Hursthouse, M. B. *J. Chem. Soc., Dalton Trans.* **1987**, 2397.

(14) N-ligated Cu(II) fluorides conventionally contain H_2O or HF molecules H-bonded to the strongly basic F ligands.

(15) While the established stoichiometry-based (eq 1) composition $[(bpy)Cu(CF_3)_2]$ is correct, the exact structure of this complex is unknown. $CF_3Cu(II)$ complexes are extremely rare; see: Jacquet, J.; Salanouve, E.; Orio, M.; Vezin, H.; Blanchard, S.; Derat, E.; Desage-El Murr, M.; Fensterbank, L. *Chem. Commun.* **2014**, *50*, 10394.

(16) (a) The $[Cu(CF_3)_4]^-$ anion has been originally observed by Burton et al.[16b] and structurally characterized by Naumann's group.[16c] (b) Willert-Porada, M. A.; Burton, D. J.; Baenziger, N. C. *J. Chem. Soc., Chem. Commun.* **1989**, 1633. (c) Naumann, D.; Roy, T.; Tebbe, K.-F.; Crump, W. *Angew. Chem., Int. Ed. Engl.* **1993**, *32*, 1482.

(17) $[(bpy)Cu(CF_3)_3]$ has been recently synthesized by an independent route and structurally characterized in our laboratories. Results of these studies will be reported separately.

(18) Morimoto, H.; Tsubogo, T.; Litvinas, N. D.; Hartwig, J. F. *Angew. Chem., Int. Ed.* **2011**, *50*, 3793.

(19) Dubinina, G. G.; Ogikubo, J.; Vicic, D. A. *Organometallics* **2008**, *27*, 6233.

(20) These diamagnetic $CF_3Cu(I)$ and $CF_3Cu(III)$ complexes are NMR-observable evidently due to a lack of fast exchange between them and paramagnetic Cu(II) species in the system.

(21) Wyss, C. M.; Tate, B. K.; Bacsa, J.; Gray, T. G.; Sadighi, J. P. *Angew. Chem., Int. Ed.* **2013**, *52*, 12920.

(22) (a) The disproportionation in our system is not driven by an irreversible process such as the intramolecular aromatic cupration in the formation of Cu(I) and Cu(III) from Cu(II) and a macrocyclic arene ligand.[9g,22b−e] (b) Ribas, X.; Jackson, D. A.; Donnadieu, B.; Mahía, J.; Parella, T.; Xifra, R.; Hedman, B.; Hodgson, K. O.; Llobet, A.; Stack, T. D. P. *Angew. Chem., Int. Ed.* **2002**, *41*, 2991. (c) Xifra, R.; Ribas, X.; Llobet, A.; Poater, A.; Duran, M.; Solà, M.; Stack, T. D. P.; Benet-Buchholz, J.; Donnadieu, B.; Mahía, J.; Parella, T. *Chem.—Eur. J.* **2005**, *11*, 5146. (d) King, A. E.; Huffman, L. M.; Casitas, A.; Costas, M.; Ribas, X.; Stahl, S. S. *J. Am. Chem. Soc.* **2010**, *132*, 12068. (e) Casitas, A.; King, A. E.; Parella, T.; Costas, M.; Stahl, S. S.; Ribas, X. *Chem. Sci.* **2010**, *1*, 326.

(23) Konovalov, A. I.; Lishchynskyi, A.; Grushin, V. V. *J. Am. Chem. Soc.* **2014**, *136*, 13410.

(24) We have developed an efficient protocol for oxidative trifluoromethylation of a broad variety of arylboronic acids and 1-alkynes with **1**-$TMSCF_3$. These results will be reported separately.

dx.doi.org/10.1021/ja5103508 | *J. Am. Chem. Soc.* XXXX, XXX, XXX−XXX