JACS
JOURNAL OF THE AMERICAN CHEMICAL SOCIETY

Communication

pubs.acs.org/JACS

Enantioselective Copper-Catalyzed Intermolecular Cyanotrifluoromethylation of Alkenes via Radical Process

Fei Wang,[†] Dinghai Wang,[†] Xiaolong Wan,[‡] Lianqian Wu,[†] Pinhong Chen,[†] and Guosheng Liu*[,†]

[†]State Key Laboratory of Organometallic Chemistry, Shanghai Institute of Organic Chemistry, University of Chinese Academy of Sciences, Chinese Academy of Sciences, 345 Lingling Road, Shanghai, China, 200032

[‡]Shanghai Institute of Organic Chemistry, Chinese Academy of Sciences, 345 Lingling Road, Shanghai, China, 200032

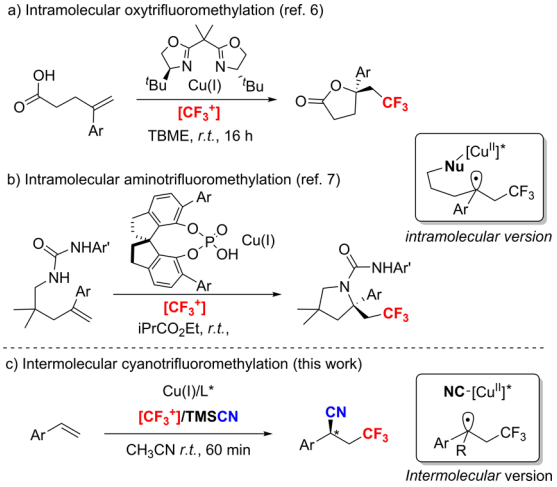
Supporting Information

ABSTRACT: A novel enantioselective copper-catalyzed intermolecular cyanotrifluoromethylation of alkenes has been developed, in which a variety of CF_3-containing alkylnitriles are furnished with excellent enantiomeric excess. Preliminary mechanistic studies revealed (1) the reaction was initiated by a SET process between activated Togni's CF_3^+ reagent and a Cu(I) catalyst; (2) the released CF_3 radical readily added to styrene to provide a benzylic radical, which was then trapped by a chiral Cu(II) cyanide species to deliver the desired alkylnitriles; (3) a low concentration of the CN anion was crucial to obtain high enantioselectivity.

Difunctionalization of alkenes has proved to be a powerful tool for constructing two vicinal carbon−carbon and carbon−heteroatom bonds in a single step from simple precursors, which significantly enhanced the molecular complexity with excellent step economy.[1] Among the reported methods, the atom transfer radical addition (ATRA) reaction is featured as one of most efficient strategies for the difunctionalization of alkenes and has received much attention in recent decades.[2] Apart from the pioneering work for introducing carbon−halide bonds, the concept of ATRA has been widely broadened with the unremitting endeavors of chemists. However, due to the extreme difficulty related to the stereochemical control of a highly reactive alkyl radical intermediate, successful *enantioselective* ATRA-type reactions of alkenes are still quite limited.[3]

Recently, a number of CF_3 radical initiated ATRA-type reactions, catalyzed by a copper complex, have been reported as an efficient protocol to build a variety of CF_3-containing molecules.[4,5] Given the prevalence of the CF_3 group in pharmaceuticals, materials, and agriculture chemicals, asymmetric trifluoromethylation of alkenes has attracted much attention; meanwhile, only two successful enantioselective examples limited to the intramolecular version have been reported: (1) in 2013, Buchwald et al. reported pioneering work on asymmetric oxytrifluoro-methylation of alkenes in the presence of a chiral bisoxazoline/Cu(I) catalyst, producing various functionalized γ- or δ-lactones with good enantioselectivity (typically <85% ee, Scheme 1a);[6] (2) Liu et al. recently discovered an enantioselective aminotrifluoromethylation of alkenes with a chiral phosphoric acid/Cu(I) catalyst, and the reactions provided excellent enantioselectivity (up to 97% ee), but generally with long reaction times (3−4 days, Scheme 1b).[7] In these reactions, the tethered carboxylic acid and amine units played an important role in promoting an enantioselective reaction between an organic radical and chiral Cu(II) species. In contrast, the more challenging intermolecular reaction remains unexplored. Herein, we report our realization of highly enantioselective intermolecular cyanotrifluoromethylation of styrenes in the presence of a chiral bisoxazoline/Cu(I) catalyst to provide a variety of enantiomeric enriched CF_3-substituted arylacetonitriles (up to 99% ee) with high efficiency (e.g., 1 mol % catalyst, within 1 h under rt, Scheme 1c).

Scheme 1. Asymmetric Cu-Catalyzed CF_3 Radical Initiated ATRA Reactions



Recently, we discovered a copper-catalyzed enantioselective cyanation of benzylic C−H bonds via a radical relay process,[8] in which a diffusible organic radical, generated from hydride atom radical abstraction, could rapidly react with a chiral copper cyanide species to form a C−CN bond with excellent enantioselectivity. Meanwhile, the alkyl radical species, generated from addition of a CF_3 radical to alkenes, was also proposed as a key intermediate in our previously reported ATRA-type reactions.[9] We speculated that, if the trapping alkyl radical by chiral copper cyanide species could be compatible in these reactions, the asymmetric cyanotrifluoromethylation of alkenes might be expected to deliver optical CF_3-containing alkyl nitriles. Given the formidable challenge of enantioselective ATRA

Received: October 7, 2016
Published: November 14, 2016

DOI: 10.1021/jacs.6b10468
J. Am. Chem. Soc. 2016, 138, 15547−15550

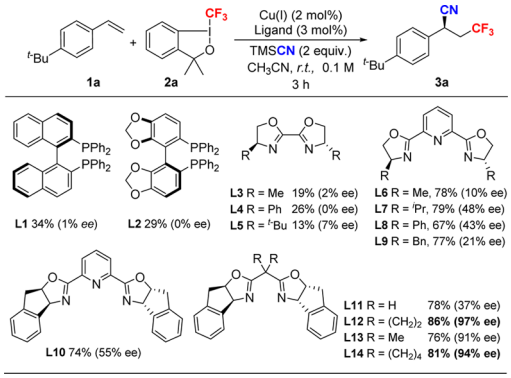
reactions, we believed that this investigation should be of great interest.

Based on our previous catalytic system,[9c] we commenced to investigate different types of chiral ligands in the presence of the $Cu(CH_3CN)_4PF_6$ catalyst (Scheme 2). Phosphine ligands **L1**–**L2** and bisoxazoline ligands **L3**–**L5** only showed poor reactivity as well as low enantioselectivity. In contrast, Py-Box type ligands **L6**–**L10** performed better reactivities to provide **3a** in good yields, but with poor to moderate enantioselectivity. Further ligand screening was focused on the 1,3-bis-2-oxazoline ligands; **L11**–**L14** with the indan group were proven to be privileged ligands, and ligand **L12** was able to catalyze the reaction in good yield (86%) and excellent ee (97%). Ligand **L11** with a methylene group provided poor enantioselectivity (37% ee). Further optimization of reaction conditions indicated that some reaction parameters, such as solvent, copper catalyst, and temperature, have less impact on the enantioselectivity (see Supporting Information (SI)). Notably, a trace amount (less than 5%) of side product, derived from homocoupling of the benzylic radical, was detected in all of the above reactions. Furthermore, when the copper catalyst loading was lowered to 1 mol %, an identical result could also be obtained after a slightly prolonged reaction time. However, other inorganic cyanides, such as NaCN and KCN, failed to provide the desired product **3a**, indicating that the mutual activation of TMSCN and Togni's $[CF_3^+]$ reagent was very important for the transformation.[9a–d]

With the optimized reaction conditions in hand, the substrate scope of styrenes was explored in the presence of 1 mol % of the copper catalyst, and the results were summarized in Table 1. A series of styrenes, with various substituents on the aromatic ring, were found to be suitable candidates to provide the corresponding products **3a**–**3s** in good to excellent yields and excellent ee. And an array of functional groups, such as halogen, ester, ether, carboxylic acid, and amide, were compatible with the reaction conditions. Importantly, compared to *para*- and *meso*-substituted styrenes, *ortho*-substituted substrates exhibited a higher enantioselectivity (**3l**–**3n** and **3q**). In addition, α- and β-vinyl naphthylenes and vinylfluorene were also tolerated under the reaction conditions to give products **3t**–**3w** with excellent results. In contrast, slightly lower enantioselectivities were observed in the cases of vinyl heteroarenes (88% ee for **3x** and 72% ee for **3y**). Finally, for the complex styrene substrates, excellent stereoselectivities were also observed to generate products **3z** (98% de) and **4a** (95% de). The absolute configurations of (*S*)-**3e** and (*S*)-**3p** were determined by X-ray.[10] However, the present protocol suffered from some limitations: (a) the 1,1-disubstituted alkene exhibited poor reactivity (**4b**); (b) terminal alkenes with an alkyl substituent provided good reactivity but poor enantioselectivities (**4c**–**4e**).

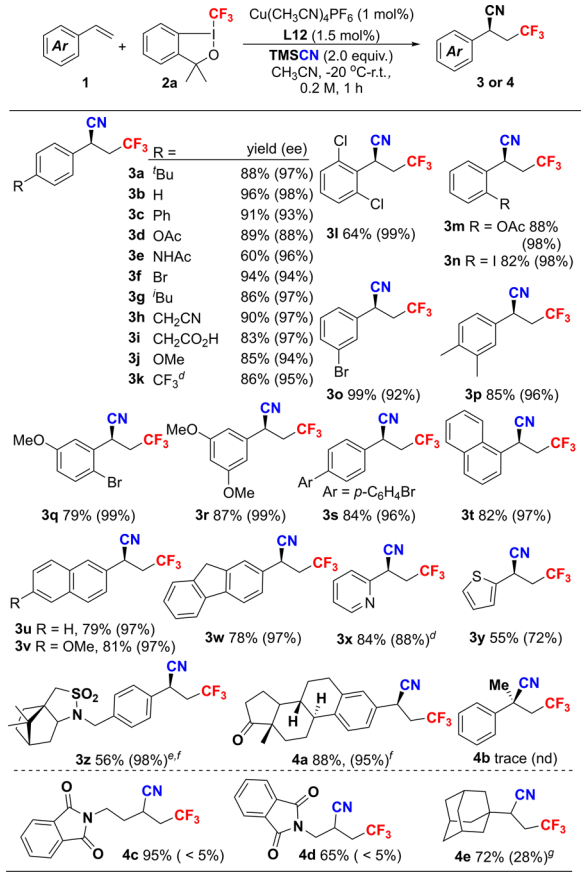
It was worth noting that, without further purification after the standard trifluoromethylation, the related amine derivatives **5** could be obtained directly in 72% yield and 95% ee with sequential hydrogenation over a Raney nickel catalyst (eq 1; for details, see SI). Interestingly, when internal alkenes, β-methylstyrene *Z*-**6** and *E*-**6**, were treated under standard reaction condition, both reactions gave identical results to yield isomers *anti*-**7** and *syn*-**7**

Scheme 2. Ligand Screening[a,b]

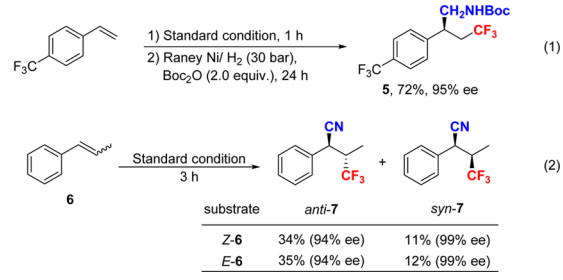


[a]All reactions were conducted in 0.1 mmol scale with $Cu(CH_3CN)_4PF_6$ as catalyst. [b]Yield was determined by ^{19}F NMR with CF_3–DMAc as internal standard.

Table 1. Substrate Scope[a,b,c]



[a]Reaction condition: substrate (0.4 mmol), **2a** (0.6 mmol), TMSCN (0.8 mmol), $Cu(CH_3CN)_4PF_6$ (0.004 mmol, 1 mol %), **L12** (0.006 mmol, 1.5 mol %), CH_3CN (2.0 mL) at −20 °C to rt. [b]Isolated yield. [c]Enantiomeric excess (*e.e.*) determined by HPLC on a chiral stationary phase. [d]ee of the crude product. [e]0.2 mmol scale. [f]Diastereoselective excess (*d.e.*). [g]Enantiomeric excess was determined by GC on a chiral stationary phase.



DOI: 10.1021/jacs.6b10468
J. Am. Chem. Soc. 2016, 138, 15547–15550

with excellent enantioselectivity, but in moderate yield (eq 2). In addition, the minor isomer, *syn*-(1*S*,2*R*)-**7**, presented a higher enantioselectivity than that of the major product, *anti*-(1*S*,2*S*)-**7**. The differences in enantiomeric ratio and yield of diastereomers *anti*-**7** and *syn*-**7** probably reflect a matched−mismatched effect between the ligand and organic radical intermediates.

To gain insight into the mechanism, a set of control experiments were conducted. For the possibility of a radical pathway, the standard reaction was dramatically inhibited by adding radical scavengers, such as Tempo or $PhN(O)CO_2Me$ (NO), and the corresponding benzyl NO−C and NO−CF_3 bond formation products were obtained (see SI). Combined with the results in eq 2, these observations were consistent with the involvement of CF_3 and benzyl radicals in the catalytic system.

Additional studies were conducted to provide further mechanistic insights. We were surprised to observe an obvious induction period in the time course studies, which was monitored by ^{19}F NMR. During this period, only a side product, derived from the homocoupling of benzyl radical species, was detected. Interestingly, when a different amount of extraneous cyanide (Bu_4NCN, 0.4−2 mol %) was added to the catalytic system, the induction period is significantly shortened, and finally disappeared (Figure 1a). Within this Bu_4NCN loading range, the

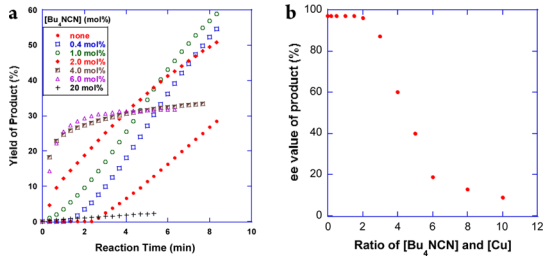


Figure 1. Extra cyanide effect on the reaction rates (a) and ee values (b). Extraneous Bu_4NCN (0−20 mol %) was added to the standard reaction using 2 mol % copper catalyst loading (**L12**:Cu = 1.5:1) at −10 °C.

same ee (97%) of the product was obtained, while the enantioselectivity decreased dramatically with the further increase of Bu_4NCN (Figure 1b). Importantly, when Bu_4NCN was increased to 20 mol % (10 times of Cu catalyst), the reaction proceeded with a much lower reaction rate to furnish the desired product with a low ee (<15%) value (Figure 1). We reasoned that a relatively high concentration of cyanide negatively affected the coordination between the catalyst and chiral ligand, resulting in the dissociation of **L12** from the copper center, which was supported by individual ^1H NMR experiments (see SI). These observations indicated that the low concentration of cyanide in the reaction system was vital for excellent enantioselective control, and the mutual activation between $[CF_3^+]$ and TMSCN presents a good reaction mode to release cyanide slowly. Furthermore, the enantioselectivity of the product was proportional to the enantiomeric excess of the chiral ligand. The absence of nonlinear effects supported that the active catalyst species for the chiral induction was consistent with a 1:1 ratio of the copper catalyst and ligand (see SI).

Furthermore, the ligand effect on the enantiomeric excess of product was also evaluated (Figure 2a). We were surprised to find that the ee of **3a** was retained with various ratios of **L12** and the Cu catalyst, even in the case of **L12** being slightly less than the catalyst. Meanwhile, the ligand effect on the induction period was also observed, which was prolonged with an increased amount of **L12** (Figure 2b). However, there is no induction period in the absence

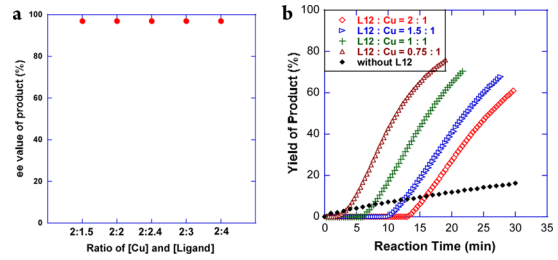
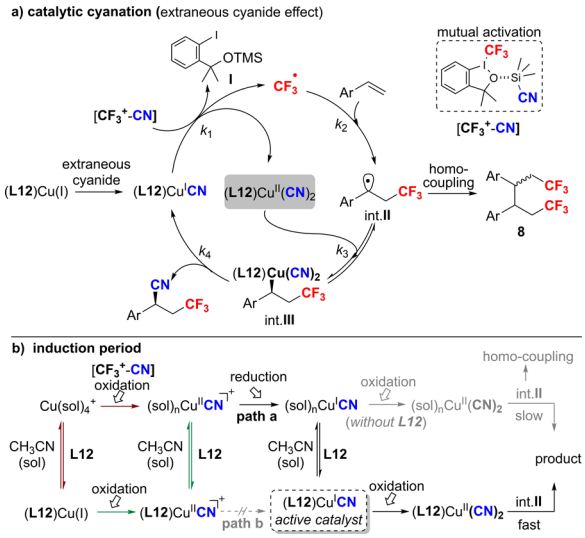


Figure 2. Ligand effect on the ee values of the product (a) and reaction rates (b).

of ligand **L12**, but the reaction proceeded with a much slower rate to give product in low yield (19%), accompanied by a significant amount of the side benzylic radical self-coupling product **8** (15% yield).

Based on the above observations, the proposed mechanism is shown in Scheme 3. Owing to the shortened induction period

Scheme 3. Proposed Mechanism



with addition of extraneous cyanide (Figure 1a), we believed that the newly formed (**L12**)Cu^ICN could act as an active catalyst undergoing the initial single electron transfer (SET) with the mutual activated [CF_3^+−**CN**] complex to generate (**L12**)-$Cu^{II}(CN)_2$ and the CF_3 radical. The latter rapidly added to styrene to yield benzylic radical int.**II**, which combined with (**L12**)$Cu^{II}(CN)_2$ to yield Cu(III) species int.**III**.[11] The final reductive elimination of int.**III** provided desired C−CN bond-forming product **3** in excellent enantiomeric excess (Scheme 3a).[8,12]

The relationship of the induction period and ligand loading shown in Figure 2b suggested that the dissociation of **L12** from the Cu center to give (sol)Cu^I (brown arrow) or (sol)$Cu^{II}CN$ (green arrow) species could be the key step for the generation of active (**L12**)Cu^ICN catalyst species. The generated (sol)$Cu^{II}CN$ was sequentially reduced and recoordinated with **L12** to give (**L12**)Cu^ICN (path a).[13] In contrast, the direct transformation from (**L12**)$Cu^{II}CN$ to (**L12**)Cu^ICN (path b) is unlikely. One rational reason is that free Cu^{II} can be readily reduced to Cu^I in the presence of a cyanide anion, but the related bidentate nitrogen ligated Cu^{II} cyanide is quite stable.[14] Thus, in the absence of **L12**, (sol)Cu^ICN can be readily obtained via path a and then oxidized to the (sol)$Cu^{II}(CN)_2$ species, which further reacts with a

DOI: 10.1021/jacs.6b10468
J. Am. Chem. Soc. 2016, 138, 15547−15550

benzylic radical to deliver product without a reduction period. However, in comparison with the (**L12**)$Cu^{II}(CN)_2$ species, (sol)$Cu^{II}(CN)_2$ showed much lower reactivity, thus resulting in a low yield of cyanation product, and a significant amount of homocoupling side product **8** simultaneously. Finally, we must mention that the detailed mechanism, especially for the generation of active Cu(I)CN species, is currently unclear.

In summary, we have developed a novel copper-catalyzed enantioselective cyanotrifluoromethylation of alkenes, which exhibited good substrate scope and functional group compatibility. A variety of CF_3-containing organonitriles were obtained with excellent enantiomeric excess under mild reaction conditions, with a low catalyst loading. Preliminary mechanistic studies demonstrated that the enantioselective C−CN bond formation possibly results from reaction of the active (**L12**)-$Cu^{II}(CN)_2$ species with a benzyl radical. Further detailed mechanistic studies and applications based on this chemistry are in progress in our laboratory.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/jacs.6b10468.

Synthetic procedures, characterization, mechanistic study data, and additional data (PDF)
Crystallographic data for **3p** (CIF)
Crystallographic data for **3e** (CIF)

■ AUTHOR INFORMATION

Corresponding Author

*gliu@mail.sioc.ac.cn

ORCID

Guosheng Liu: 0000-0003-0572-9370

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We thank National Basic Research Program of China (973-2015CB856600), the National Nature Science Foundation of China (Nos. 21225210, 21532009, 21421091, and 21472217), and the strategic Priority Research Program of the Chinese Academy of Sciences (No. XDB20000000) for financial support.

■ REFERENCES

(1) (a) Beller, M.; Seayad, J.; Tillack, A.; Jiao, H. *Angew. Chem., Int. Ed.* **2004**, *43*, 3368. (b) Jensen, K. H.; Sigman, M. S. *Org. Biomol. Chem.* **2008**, *6*, 4083. (c) McDonald, R. I.; Liu, G.; Stahl, S. S. *Chem. Rev.* **2011**, *111*, 2981.

(2) (a) Minisci, F. *Acc. Chem. Res.* **1975**, *8*, 165. (b) Pintauer, T. *Eur. J. Inorg. Chem.* **2010**, *2010*, 2449. (c) Muñoz-Molina, J. M.; Belderrain, T. R.; Pérez, P. J. *Eur. J. Inorg. Chem.* **2011**, *2011*, 3155. (d) Zhang, N.; Samanta, S. R.; Rosen, B. M.; Percec, V. *Chem. Rev.* **2014**, *114*, 5848.

(3) For leading examples on transition metal-catalyzed asymmetric ATRA reactions, see: (a) Murai, S.; Sugise, R.; Sonoda, N. *Angew. Chem., Int. Ed. Engl.* **1981**, *20*, 475. (b) Kameyama, M.; Kamigata, N.; Kobayashi, M. *J. Org. Chem.* **1987**, *52*, 3312. (c) Iizuka, Y.; Li, Z.; Satoh, K.; Kamigaito, M.; Okamoto, Y.; Ito, J.; Nishiyama, H. *Eur. J. Org. Chem.* **2007**, *2007*, 782.

(4) For some reviews, see: (a) Chen, P.; Liu, G. *Synthesis* **2013**, *45*, 2919. (b) Liu, T.; Shen, Q. *Eur. J. Org. Chem.* **2012**, *2012*, 6679. (c) Wu, X.-F.; Neumann, H.; Beller, M. *Chem. - Asian J.* **2012**, *7*, 1744.

(5) For some recent examples, see: (a) Shimizu, R.; Egami, H.; Hamashima, Y.; Sodeoka, M. *Angew. Chem., Int. Ed.* **2012**, *51*, 4577. (b) Mizuta, S.; Galicia-López, O.; Engle, K. M.; Verhoog, S.; Wheelhouse, K.; Rassias, G.; Gouverneur, V. *Chem. - Eur. J.* **2012**, *18*, 8583. (c) Janson, P. G.; Ghoneim, I.; Ilchenko, N. O.; Szabó, K. J. *Org. Lett.* **2012**, *14*, 2882. (d) Li, Y.; Studer, A. *Angew. Chem., Int. Ed.* **2012**, *51*, 8221. (e) Yasu, Y.; Koike, T.; Akita, M. *Angew. Chem., Int. Ed.* **2012**, *51*, 9567. (f) Zhu, R.; Buchwald, S. L. *J. Am. Chem. Soc.* **2012**, *134*, 12462. (g) Feng, C.; Loh, T.-P. *Chem. Sci.* **2012**, *3*, 3458. (h) Mizuta, S.; Verhoog, S.; Engle, K. M.; Khotavivattana, T.; O'Duill, M.; Wheelhouse, K.; Rassias, G.; Médebielle, M.; Gouverneur, V. *J. Am. Chem. Soc.* **2013**, *135*, 2505. (i) Wu, X.; Chu, L.; Qing, F.-L. *Angew. Chem., Int. Ed.* **2013**, *52*, 2198. (j) Egami, H.; Kawamura, S.; Miyazaki, A.; Sodeoka, M. *Angew. Chem., Int. Ed.* **2013**, *52*, 7841. (k) Feng, C.; Loh, T.-P. *Angew. Chem., Int. Ed.* **2013**, *52*, 12414. (l) Ilchenko, N. O.; Janson, P. G.; Szabó, K. J. *Chem. Commun.* **2013**, *49*, 6614. (m) Li, L.; Deng, M.; Zheng, S.-C.; Xiong, Y.-P.; Tan, B.; Liu, X.-Y. *Org. Lett.* **2014**, *16*, 504. (n) Yang, F.; Klumphu, P.; Liang, Y.-M.; Lipshutz, B. H. *Chem. Commun.* **2014**, *50*, 936. (o) Kawamura, S.; Egami, H.; Sodeoka, M. *J. Am. Chem. Soc.* **2015**, *137*, 4865.

(6) (a) Zhu, R.; Buchwald, S. L. *Angew. Chem., Int. Ed.* **2013**, *52*, 12655. (b) Zhu, R.; Buchwald, S. L. *J. Am. Chem. Soc.* **2015**, *137*, 8069.

(7) Lin, J.-S.; Dong, X.-Y.; Li, T.-T.; Jiang, N.-C.; Tan, B.; Liu, X.-Y. *J. Am. Chem. Soc.* **2016**, *138*, 9357.

(8) Zhang, W.; Wang, F.; McCann, S. D.; Wang, D.; Chen, P.; Stahl, S. S.; Liu, G. *Science* **2016**, *353*, 1014.

(9) (a) Wang, F.; Qi, X.; Liang, Z.; Chen, P.; Liu, G. *Angew. Chem., Int. Ed.* **2014**, *53*, 1881. (b) Wang, F.; Wang, D.; Mu, X.; Chen, P.; Liu, G. *J. Am. Chem. Soc.* **2014**, *136*, 10202. (c) Liang, Z.; Wang, F.; Chen, P.; Liu, G. *J. Fluorine Chem.* **2014**, *167*, 55. (d) Liang, Z.; Wang, F.; Chen, P.; Liu, G. *Org. Lett.* **2015**, *17*, 2438. For similar studies, see: (e) Ilchenko, N. O.; Janson, P. G.; Szabó, K. J. *J. Org. Chem.* **2013**, *78*, 11087. (f) He, Y.-T.; Li, L.-H.; Yang, Y.-F.; Zhou, Z.-Z.; Hua, H.-L.; Liu, X.-Y.; Liang, Y.-M. *Org. Lett.* **2014**, *16*, 270. (g) Ratani, T. S.; Bachman, S.; Fu, G. C.; Peters, J. C. *J. Am. Chem. Soc.* **2015**, *137*, 13902.

(10) CCDC 1502693 [(*S*)-**3e**] and CCDC 1502694 [(*S*)-**3p**] contain the supplementary crystallographic data, which can be obtained free of charge from the Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/services/structure_deposit/cif.

(11) For transition-metal-catalyzed enantioselective cross-coupling reactions involving the combination of an alkyl radical with a chiral metal complex, see: (a) Fischer, C.; Fu, G. C. *J. Am. Chem. Soc.* **2005**, *127*, 4594. (b) Schley, N. D.; Fu, G. C. *J. Am. Chem. Soc.* **2014**, *136*, 16588. (c) Mao, J.; Liu, F.; Wang, M.; Wu, L.; Zheng, B.; Liu, S.; Zhong, J.; Bian, Q.; Walsh, P. J. *J. Am. Chem. Soc.* **2014**, *136*, 17662. (d) Jin, M.; Adak, L.; Nakamura, M. *J. Am. Chem. Soc.* **2015**, *137*, 7128. (e) Kainz, Q. M.; Matier, C. D.; Bartoszewicz, A.; Zultanski, S. L.; Peters, J. C.; Fu, G. C. *Science* **2016**, *351*, 681. (f) Zuo, Z.; Cong, H.; Li, W.; Choi, J.; Fu, G. C.; MacMillan, D. W. C. *J. Am. Chem. Soc.* **2016**, *138*, 1832.

(12) The similar pathway was also reported in the Ni-catalyzed reaction; see: Gutierrez, O.; Tellis, J. C.; Primer, D. N.; Molander, G. A.; Kozlowski, M. C. *J. Am. Chem. Soc.* **2015**, *137*, 4896.

(13) There are some reports on the reduction of Cu^{II} to Cu^{I}; see: (a) Franc, G.; Jutand, A. *Dalton Trans.* **2010**, *39*, 7873. (b) Yi, H.; Zhang, G.; Xin, J.; Deng, Y.; Miller, J. T.; Kropf, A. J.; Bunel, E. E.; Qi, X.; Lan, Y.; Lee, J.-F.; Lei, A. *Chem. Commun.* **2016**, *52*, 6914. Alternatively, the formation of Cu^{I} from Cu^{II} could be achieved through disproportionation process; see: (c) Ribas, X.; Jackson, D. A.; Donnadieu, B.; Mahia, J.; Parella, T.; Xifra, R.; Hedman, B.; Hodgson, K. O.; Llobet, A.; Stack, T. D. P. *Angew. Chem., Int. Ed.* **2002**, *41*, 2991. (d) King, A. E.; Huffman, L. M.; Casitas, A.; Costas, M.; Ribas, X.; Stahl, S. S. *J. Am. Chem. Soc.* **2010**, *132*, 12068. (e) Zhang, H.; Yao, B.; Zhao, L.; Wang, D.-X.; Xu, B.-Q.; Wang, M.-X. *J. Am. Chem. Soc.* **2014**, *136*, 6326.

(14) The simple copper(II) cyanide is unstable at normal temperature and cannot be isolated; see: (a) Cotton, F. A.; Wilkinson, G. *Advanced Inorganic Chemistry*, 3rd ed.; Interscience: New York, NY, 1972; p 907. (b) Longo, A.; Buch, T. *Inorg. Chem.* **1967**, *6*, 556. The nitrogen-based ligand could effectively stabilize the copper(II) cyanide complex; see: (c) Wicholas, M.; Wolford, T. *Inorg. Chem.* **1974**, *13*, 316. (d) Anderson, O. P. *Inorg. Chem.* **1975**, *14*, 730 and references therein.

DOI: 10.1021/jacs.6b10468
J. Am. Chem. Soc. 2016, 138, 15547−15550