Radical Reactions

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Silver-Catalyzed Cross-Coupling of Isocyanides and Active Methylene Compounds by a Radical Process

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Abstract: *Isocyanides are versatile building blocks, and have been extensively exploited in C–H functionalization reactions. However, transition-metal-catalyzed direct C–H functionalization reactions with isocyanides suffer from over-insertion of isocyanides. Reported herein is a radical coupling/isomerization strategy for the cross-coupling of isocyanides with active methylene compounds through silver-catalysis. The method solves the over-insertion issue and affords a variety of otherwise difficult to synthesize β-aminoenones and tricarbonylmethanes under base- and ligand-free conditions. This report presents a new fundamental C–C bond-forming reaction of two basic chemicals.*

Carbon–carbon bond formation is fundamentally important in organic synthesis. Transition-metal-catalyzed functionalization of C–H bonds is emerging as a very powerful methodology for C–C bond formation and has received a lot of attention in recent years.[1] Despite the substantial advances, development of novel C–C coupling reactions of two basic chemicals is still highly appealing. Isocyanides are versatile building blocks in organic synthesis because of the carbene-like reactivity of the isocyano group.[2] Besides the consistent prosperity of isocyanides in multicomponent reactions,[3] they recently have been extensively exploited in C–H functionalization reactions.[4] In this context, the uncontrollable over-insertion of isocyanides is a serious issue for transition-metal-catalyzed intermolecular C–H functionalization (Figure 1a).[2a,5] As a result, isocyanide-involved C–H functionalizations reported so far have usually appeared as an intrinsic part of tandem cyclization reactions, and represent a valuable methodology for assembling various hetero- and carbocyclic compounds.[6] In stark contrast, reports on transition-metal-catalyzed C–H functionalization for cross-coupling reactions of isocyanides, without subsequent cyclization, are considerably rare.[7–11] Hitherto, only three such reactions have been established: 1) the cyanation of indoles and 2-aryl/-alkenyl pyridines;[7] 2) the carbamoylation of tertiary amines,[8] aldehydes,[9] and indoles;[10] and 3) the imidization of terminal alkynes.[11] All these reactions require either specific alignment of substrate structure or special catalysts, and moreover C_{sp3}–H functionalization is restricted to carbamoylation of the tertiary amines.[8] Therefore, the discovery of an effective strategy which is capable of expanding the repertoire of isocyanide-involved C–H functionalization, in particular for C_{sp3}–H bonds, remains highly desirable.

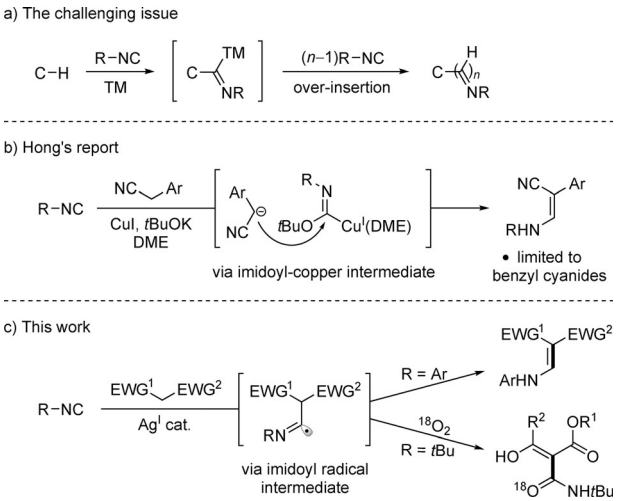

Figure 1. Isocyanides in direct C–H functionalization through a coupling/isomerization sequence.

After the gold rush[12] and traditional copper catalysis,[13] silver catalysis is emerging as an active area in organic synthesis,[14] particularly in radical reactions.[15] Herein, we report a novel radical coupling/isomerization strategy for the C–C cross-coupling of isocyanides and active methylene compounds.[16] The over-insertion of isocyanides, which is most frequently encountered in the transition-metal-catalyzed direct C–H functionalization with isocyanides, can be skillfully avoided by this strategy. During this manuscript preparation, Hong et al. reported a formal coupling/isomerization of isocyanides and benzyl cyanides, in which a new C–C bond is formed indirectly by addition of a carboanion to an imidoyl copper intermediate (Figure 1b).[17] In our present work, the C–C coupling event directly occurs by a radical addition process with the generation of an imidoyl radical intermediate (Figure 1c). A variety of otherwise difficult to synthesize β-aminoenones and tricarbonylmethanes are efficiently prepared in an isocyanide-dependent approach, under base- and ligand-free conditions.

The reaction between *p*-methoxyphenyl isonitrile (**1a**) and ethyl acetoacetate (**2a**) was initially investigated by varying the metal salts and solvents to optimize the protocol

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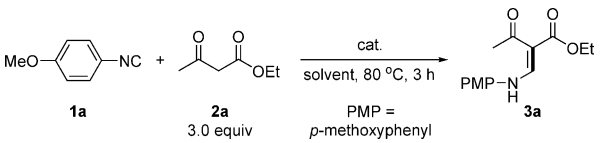
Table 1: Optimization of the reaction conditions.[a]



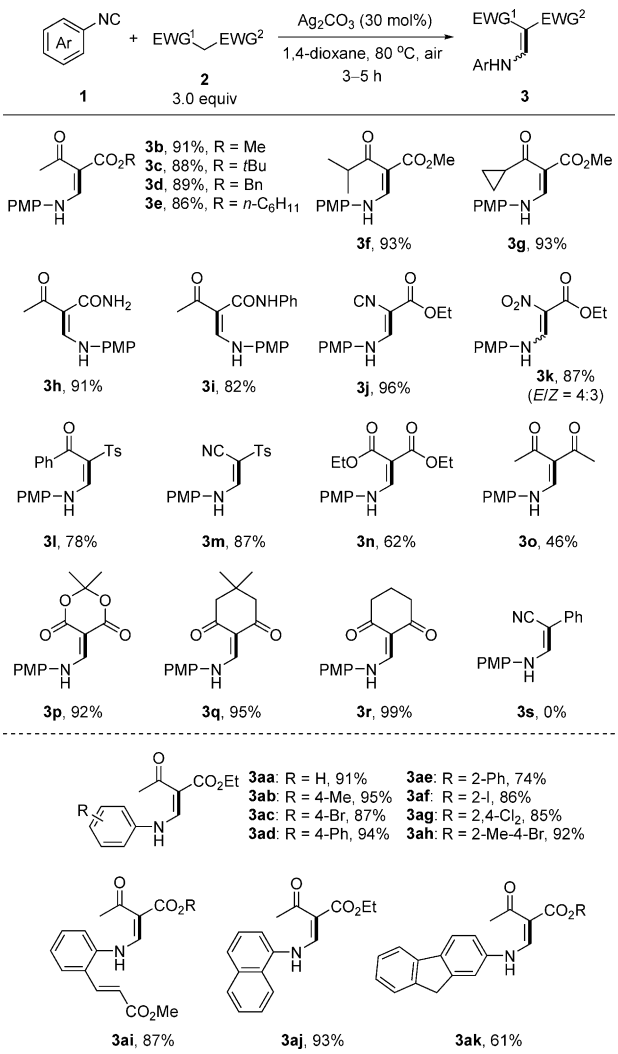
1a **2a** 3.0 equiv PMP = *p*-methoxyphenyl **3a**

Entry	Cat.	Amount	Solvent	Yield [%][b]
1	AgOTf	30 mol%	1,4-dioxane	25
2	Ag_2O	30 mol%	1,4-dioxane	43
3	AgF	30 mol%	1,4-dioxane	51
4	AgOAc	30 mol%	1,4-dioxane	76
5	Ag_2CO_3	30 mol%	1,4-dioxane	92
6	Ag_2CO_3	10 mol%	1,4-dioxane	48 (52)[c]
7	$Pd(OAc)_2$	30 mol%	1,4-dioxane	0[d]
8	CuI	30 mol%	1,4-dioxane	0[d]
9	$Mn(OAc)_3$	30 mol%	1,4-Dioxane	0[d]
10	Ag_2CO_3	30 mol%	CH_3CN	78
11	Ag_2CO_3	30 mol%	DCE	21
12	Ag_2CO_3	30 mol%	DMSO	15
13	Ag_2CO_3	30 mol%	MeOH	trace

[a] Reaction conditions: **1a** (0.5 mmol), **2a** (1.5 mmol), 1,4-Dioxane (2.0 mL), Ag_2CO_3 (0.15 mmol), 80 °C for 3 h. [b] Yield of the isolated product. [c] In the presence of 10 mol% Ag_2CO_3; yield calculated from the ^{1}H NMR spectrum and the amount of unreacted substrate **1a** within parentheses. [d] Resulting in an unidentified mixture. No **3a** was detected by ^{1}H NMR analysis of the mixture. DCE = 1,2-dichloroethane, DMSO = dimethyl sulfoxide.

(Table 1). Only the silver salts were effective in catalyzing the coupling of the isocyanide to the active methylene group, with Ag_2CO_3 being the best and thus affording the *N*-*p*-methoxyphenyl-β-aminoenone (**3a**) in 92% yield (entries 1–5). The quantity of the Ag_2CO_3 catalyst played a crucial and apparent role on the efficacy of the reaction. For instance, the reaction efficiency was sharply diminished and an incomplete conversion was observed when the amount of Ag_2CO_3 used was reduced to 10 mol% (entry 6). Other metal salts such as $Pd(OAc)_2$, CuI, and $Mn(OAc)_3$ were checked for catalytic activities, and in stark contrast, all resulted in an unidentified mixture, in which the desired β-aminoenone (**3a**) was not detected by ^{1}H NMR analysis (entries 7–9). After establishing Ag_2CO_3 as the optimal catalyst, we focused on screening of the solvents. Aprotic and polar solvents such as CH_3CN, DCE, and DMSO have a deleterious effect and afforded **3a** in 15–78% yields (entries 10–12). The protic solvent MeOH resulted in only trace amounts of product (entry 13). We therefore decided to use Ag_2CO_3 (30 mol%) in 1,4-dioxane at 80 °C as the optimal reaction conditions.

With the optimal reaction conditions in hand, we explored the substrate scope with regard to different active methylene compounds and aryl isonitriles (Scheme 1). Delightfully, the substrate scope is quite general, and a wide variety of active methylene compounds, having various electron-withdrawing groups (EWGs), and aryl isonitriles can be applied to this protocol, thus affording the corresponding β-aminoenones in good to excellent yields. All the reactions proceeded smoothly when open to air and were completed within 3–5 hours. For example, when **1a** reacted with a variety of active methylene compounds, in which the methylene moiety is activated with two EWGs which are either the same or

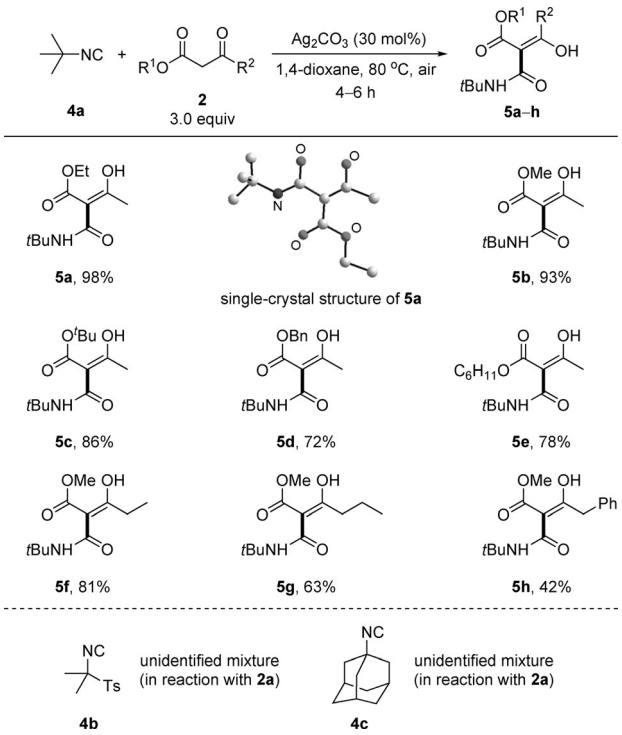


Scheme 1. Scope with respect to the active methylene compounds and aryl isonitriles.

different (carbonyl, nitro, cyano, and sulfonyl) groups, participated in the coupling reactions smoothly to afford the target *N*-aryl-β-aminoenones (**3b–o**) in 46–96% yields. The structure and stereochemistry of **3h** and **3r** were unequivocally resolved by X-ray crystallographic analysis (see the Supporting Information for details). Except for **3k**, which is a mixture of *E* and *Z* isomers in a 4:3 ratio, other substrates with different EWGs ($EWG^1 \neq EWG^2$) generated single stereoisomers such as **3b–j** and **3l–m**. Their stereochemistry was identified by NOE experiments. Interestingly, acetoacetamides (**1h** and **1i**) resulted in the products **3h** and **3i** in the *Z*-isomeric form. This unusual behavior is probably a result of the propensity of the amide group to form hydrogen bonds.[18] It is worth noting that, in addition to the acyclic active methylene compounds, cyclic substrates were also capable reacting using this protocol, and afforded the corresponding products (**3p–r**) in nearly quantitative yields. Although it is a little discouraging that the benzyl cyanide, a compound successfully utilized in Hong's work,[17] did not result in the desired product **3s** (benzyl cyanide was recovered), this result clearly suggested a different mechanism is operative in the

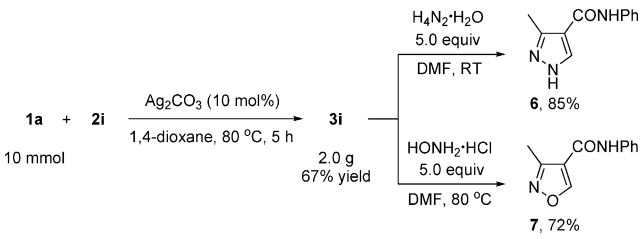
current silver-catalyzed reaction. Later, the substrate scope of this reaction was extended to other aromatic isocyanides without difficulty. The electronic properties of the aromatic rings had no influence on either the stereoselectivities or yields of the products **3aa**–**ak**, although use of 2-isocyano-9*H*-fluorene resulted in a slight decrease in the yield of corresponding product (**3ak**). All the products were obtained with an *E* configuration, and the stereochemistry was confirmed with the help of an NOE experiment involving **3ak**. It is worth mentioning that synthetic methods for enamines like **3**, which having two different EWGs, are rare.[19]

We then turned our attention to investigating the mode of reactivity and effect on the coupling reaction in the case of aliphatic isocyanides (Scheme 2). Gratifyingly, an unprecedented C_{sp3}–H carbamoylation of β-ketoesters with *tert*-butyl isocyanide (**4a**) was discovered, and led to a range of tricarbonylmethanes (**5a**–**h**) in moderate to high yields. Unfortunately, the use of other aliphatic isocyanides, which are similar in structure to **4a** (e.g., **4b** and **4c**), resulted in an unidentified mixture. The structure of **5a** was unambiguously confirmed by the single-crystal X-ray diffraction analysis. Therefore, we have developed a novel and efficient C_{sp3}–H carbamoylation of active methylene compounds.[2,4,20] This finding is of great interest as the tricarbonylmethane structure is a key structural motif for many antibiotics.[21] Herein we provide an extremely simple way to access such kind of valuable compounds.[22]

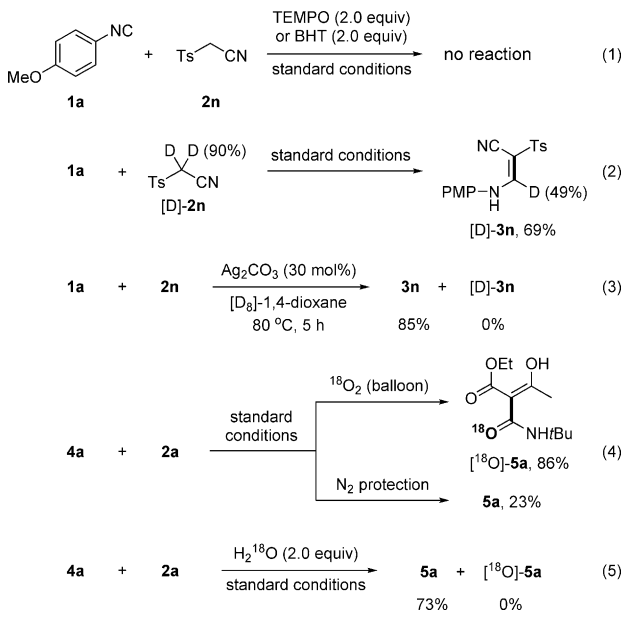


Scheme 2. The reaction of β-ketoesters with aliphatic isocyanides.[32]

A large-scale (10 mmol) synthesis was carried out under the silver-catalyzed conditions. Pleasingly, the reaction of **1a** and **2i** proceeded smoothly, even with a reduced the catalyst loading (10 mol%), albeit affording product **3i** with a slightly decreased yield. The highly functionalized alkenes generated by this protocol offer opportunities for further synthetic manipulation to access functionalized heterocyclic motifs. For instance, synthetic conversion of *N*-aryl-β-enaminamide (**3i**) into the functionalized pyrazole **6** and isoxazole **7** were attained in good yields by reacting with hydrazine hydrate and hydroxylamine hydrochloride, respectively.



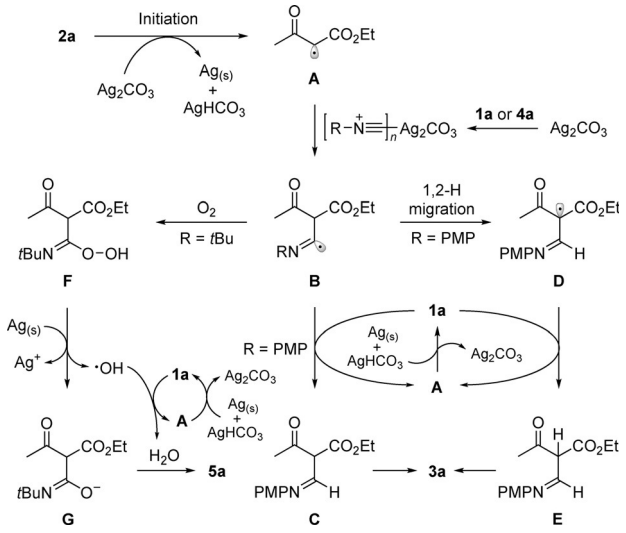
Control experiments were performed to gain insight into the reaction mechanism (Scheme 3). The cross-coupling reaction between **1a** and 2-tosylacetonitrile (**2n**) was completely suppressed by the addition of the radical inhibitor 2,2,6,6-etramethylpiperidine-N-oxyl (TEMPO) or 2,6-di-tert-butyl-hydroxytoluene (BHT),[23] thereby suggesting that the reaction goes through a free radical intermediate [Eq. (1)]. However we could not isolate adducts of the scavengers formed from radical intermediates. Deuterium-labeling studies using [D]-**2n** unambiguously confirmed the active methylene compounds as the source of the hydrogen atom in the product [Eq. (2)], wherein the erosion of deuteration in [D]-**3n** is probably due to traces of water. Further, the possibility of the solvent as the hydrogen source was excluded as no [D]-**3n** can be isolated from the reaction performed in [D_8]1,4-dioxane [Eq. (3)]. Meanwhile, to investigate the effect of O_2 on the carbamoylation reaction, we performed the reaction of **4a** and **2a** under an $^{18}O_2$ atmosphere, and expectedly [^{18}O]-**5a**



Scheme 3. Mechanistic investigations.

was obtained in 86% yield with a high degree of ^{18}O incorporation [Eq. (4)]. Furthermore, the yield of **5a** was sharply decreased to 23% (when the reaction was run under an N_2 atmosphere), thus confirming the participation of oxygen in the reaction.[24] Importantly, the addition of either the radical scavenger TEMPO or BHT to the reaction mixture of **4a** and **2a** under an oxygen atmosphere resulted in an unidentified mixture, without formation of **5a**, therefore suggesting a free radical process. Further, unlike H_2O acting as the oxygen source in previous reports on isocyanide-involved carbamoylation,[25] the reaction of **4a** with **2a** does not provided [^{18}O]-**5a** in the presence of $H_2{}^{18}O$ [Eq. (5)].

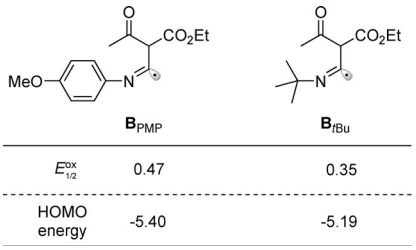
Based on the results from the experimental investigations and related literature precedents, a plausible reaction mechanism (Scheme 4) is proposed by using **2a** as a model substrate. In the radical initiation stage, the carbonate anion



Scheme 4. Plausible reaction mechanism.

of Ag_2CO_3 abstracts a proton from **2a**, thus leading to the generation of a carboanion and $AgHCO_3$, followed by further oxidation of a carboanion by an Ag^+ ion to yield the radical intermediate **A**.[15e,26] In this process, Ag_2CO_3 plays the dual role as base and one-electron oxidant. The oxidant behavior of Ag_2CO_3 was explained by the often observed silver mirror in the reactions. Meanwhile, the complex $Ag_2CO_3(RNC)_n$ may be formed[27] and react with **A** to give the imidoyl radical **B**.[6] The fate of **B**, to afford either the enamine **3a** or the tricarbonylmethane **5a**, is directly linked to the type of isocyanide. When the isonitrile is aromatic, for example **1a**, there are two possible paths for **B** to **3a** conversion. One way is direct abstraction of a hydrogen atom from **2a** by generating a new radical intermediate (**A**), thus resulting in the formation of the imine intermediate **C**, which quickly isomerizes to **3a** as the final product. Alternatively, 1,2-H migration may take place to deliver a more stable tricarbonylmethenyl radical (**D**),[28] which also abstracts a hydrogen atom from **2a** to release the intermediate **E**, which eventually isomerizes to **3a**. These two reaction pathways all reasonably account for the outcome observed for the deuterium-labeling experiment [Scheme 3, Eq. (2)]. Regarding the C_{sp3}–H carbamoylation of **1a** with **4a**, oxygenation of **B** leads to the hydroperoxide compound **F**. Afterwards, silver-promoted decomposition of **F** generates the oxyanion intermediate **G** and a hydroxyl radical.[29] The so formed hydroxyl radical could abstract a hydrogen atom from **1a** to generate **A** and H_2O for protonation of the intermediate **G** to produce the target product **5a**. All the reactions belonging to any of these two categories proceed through silver(I)-initiated autocatalysis, and finally termination of the radical species **A** to **1a** by oxidation of Ag(s) and subsequent proton abstraction from $AgHCO_3$, thereby leading to the regeneration of Ag_2CO_3 catalyst and completing the catalytic cycle.

The reason for the divergent isocyanide-dependent reactions was further elucidated by theoretical calculations.[30] As shown in Figure 2, the intermediate $\mathbf{B}_{t\mathrm{Bu}}$ shows a smaller oxidation potential than that of $\mathbf{B}_{\mathrm{PMP}}$ (0.35 versus 0.47), thus



	$\mathbf{B}_{\mathrm{PMP}}$	$\mathbf{B}_{t\mathrm{Bu}}$
$E^{ox}_{1/2}$	0.47	0.35
HOMO energy	-5.40	-5.19

Figure 2. Theoretical calculations on the oxidation potentials (V) and HOMO energies (eV) at the B3LYP/6-311G(d,p) level of theory. Calculated for 1,4-dioxane with a polarized continuum model.

suggesting it is easily subject to one-electron removal. In addition, $\mathbf{B}_{t\mathrm{Bu}}$ has much higher HOMO energy level than does $\mathbf{B}_{\mathrm{PMP}}$ (−5.19 versus −5.40),[31] and further supports the easier oxidation of $\mathbf{B}_{t\mathrm{Bu}}$, because the destabilized HOMO would lead to one-electron oxidation more smoothly.

In conclusion, an intriguing radical coupling reaction between active methylene compounds and isocyanides has been developed for the first time and involves silver catalysis. The over-insertion of isocyanides commonly observed for transition-metal-catalyzed C–H functionalization with isocyanides has been skillfully avoided by using a radical coupling/isomerization strategy. A range of otherwise difficult to synthesize β-aminoenones and tricarbonylmethanes was efficiently prepared in an isocyanide-dependent approach. A radical mechanism was proposed on the basis of preliminary mechanistic investigations. This report presents a new fundamental C–C bond-forming reaction of two basic chemicals. Studies to expand its scope and apply it to the development of multicomponent radical reactions are forthcoming.

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[1] "C–H activation": *Topics in Current Chemistry*, *Vol. 292* (Eds.: J.-Q. Yu, Z. Shi), Springer, Berlin, **2010**.
[2] For reviews, see: a) V. P. Boyarskiy, N. A. Bokach, K. V. Luzyanin, V. Y. Kukushkin, *Chem. Rev.* **2015**, *115*, 2698; b) A. V. Gulevich, A. G. Zhdanko, R. V. A. Orru, V. G. Nenajdenko, *Chem. Rev.* **2010**, *110*, 5235.
[3] For examples, see: a) T. Buyck, Q. Wang, J. Zhu, *J. Am. Chem. Soc.* **2014**, *136*, 11524; b) W. Szymański, W. A. Velema, B. L. Feringa, *Angew. Chem. Int. Ed.* **2014**, *53*, 8682; *Angew. Chem.* **2014**, *126*, 8826; c) P. Mampuys, Y. Zhu, T. Vlaar, E. Ruijter, R. V. A. Orru, B. U. W. Maes, *Angew. Chem. Int. Ed.* **2014**, *53*, 12849; *Angew. Chem.* **2014**, *126*, 13063; d) C. Lei, D. Wang, L. Zhao, J. Zhu, M. Wang, *J. Am. Chem. Soc.* **2013**, *135*, 4708.
[4] a) B. Zhang, A. Studer, *Chem. Soc. Rev.* **2015**, *44*, 3505; b) H. Wang, B. Xu, *Chin. J. Org. Chem.* **2015**, *35*, 588.
[5] For a review, see: a) F. Millich, *Chem. Rev.* **1972**, *72*, 101; See also: b) Z.-Q. Wu, R. J. Ono, Z. Chen, C. W. Bielawski, *J. Am. Chem. Soc.* **2010**, *132*, 14000; c) Y. Xue, Y. Zhu, L. Gao, X. He, N. Liu, W. Zhang, J. Yin, Y. Ding, H. Zhou, Z. Wu, *J. Am. Chem. Soc.* **2014**, *136*, 4706.
[6] a) Y. Liu, H. Xu, W. Kong, M. Shang, H. Dai, J. Yu, *Nature* **2014**, *515*, 389; b) M. Tobisu, K. Koh, T. Furukawa, N. Chatani, *Angew. Chem. Int. Ed.* **2012**, *51*, 11363; *Angew. Chem.* **2012**, *124*, 11525; c) H. Jiang, Y. Cheng, R. Wang, M. Zheng, Y. Zhang, S. Yu, *Angew. Chem. Int. Ed.* **2013**, *52*, 13289; *Angew. Chem.* **2013**, *125*, 13531; d) Z. Xia, J. Huang, Y. He, J. Zhao, J. Lei, Q. Zhu, *Org. Lett.* **2014**, *16*, 2546, and references therein.
[7] a) J. Peng, J. Zhao, Z. Hu, D. Liang, J. Huang, Q. Zhu, *Org. Lett.* **2012**, *14*, 4966; b) X. Hong, H. Wang, G. Qian, Q. Tan, B. Xu, *J. Org. Chem.* **2014**, *79*, 3228.
[8] a) X. Ye, C. Xie, R. Huang, J. Liu, *Synlett* **2012**, 409; b) M. Rueping, C. Vila, *Org. Lett.* **2013**, *15*, 2092; c) C. Xie, L. Han, *Tetrahedron Lett.* **2014**, *55*, 240.
[9] a) M. Bouma, G. Masson, J. Zhu, *J. Org. Chem.* **2010**, *75*, 2748; b) T. Soeta, Y. Kojima, Y. Ukaji, K. Inomata, *Org. Lett.* **2010**, *12*, 4341.
[10] J. Peng, L. Liu, Z. Hu, J. Huang, Q. Zhu, *Chem. Commun.* **2012**, *48*, 3772.
[11] E. Barnea, T. Andrea, M. Kapon, J.-C. Berthet, M. Ephritikhine, M. S. Eisen, *J. Am. Chem. Soc.* **2004**, *126*, 10860.
[12] For monographs, see: a) *Gold Catalysis*, *An Homogeneous Approach* (Eds.: F. D. Toste, V. Michelet), Imperial College Press, London, **2014**; b) *Modern Gold Catalyzed Synthesis* (Eds.: A. S. K. Hashmi, F. D. Toste), Wiley-VCH, Weinheim, **2012**; for a general recent overview, see: c) C. M. Friend, A. S. K. Hashmi, *Acc. Chem. Res.* **2014**, *47*, 729.
[13] For recent reviews, see: a) S. E. Allen, R. R. Walvoord, R. Padilla-Salinas, M. C. Kozlowski, *Chem. Rev.* **2013**, *113*, 6234; b) X. Guo, D. Gu, Z. Wu, W. Zhang, *Chem. Rev.* **2015**, *115*, 1622.
[14] a) *Silver in Organic Chemistry* (Ed.: M. Harmata), Wiley, Hoboken, **2010**; b) B. H. Lipshutz, Y. Yamamoto, *Chem. Rev.* **2008**, *108*, 2793; c) Y. Yamamoto, *Chem. Rev.* **2008**, *108*, 3199.
[15] For recent reviews, see: a) J. Chen, X. Yu, W. Xiao, *Synthesis* **2015**, 604; b) R. Song, Y. Liu, Y. Xie, J. Li, *Synthesis* **2015**, 1195; c) S. Tang, K. Liu, C. Liu, A. Lei, *Chem. Soc. Rev.* **2015**, *44*, 1070; d) G. Yan, M. Yang, X. Wu, *Org. Biomol. Chem.* **2013**, *11*, 7999; See also: e) P. Xu, S. Guo, L. Wang, P. Tang, *Angew. Chem. Int. Ed.* **2014**, *53*, 5955; *Angew. Chem.* **2014**, *126*, 6065; f) J. M. Alderson, A. M. Phelps, R. J. Scamp, N. S. Dolan, J. M. Schomaker, *J. Am. Chem. Soc.* **2014**, *136*, 16720; g) M. Yang, B. Su, Y. Wang, K. Chen, X. Jiang, Y. Zhang, X. Zhang, G. Chen, Y. Cheng, Z. Cao, Q. Guo, L. Wang, Z. Shi, *Nat. Commun.* **2014**, *5*, 4707; h) Z. Li, L. Song, C. Li, *J. Am. Chem. Soc.* **2013**, *135*, 4640; i) C. He, S. Guo, J. Ke, J. Hao, H. Xu, H. Chen, A. Lei, *J. Am. Chem. Soc.* **2012**, *134*, 5766; j) X. Liu, Z. Wang, X. Cheng, C. Li, *J. Am. Chem. Soc.* **2012**, *134*, 14330.
[16] For our reports on silver catalysis, see: a) Z. Liu, J. Liu, L. Zhang, P. Liao, J. Song, X. Bi, *Angew. Chem. Int. Ed.* **2014**, *53*, 5305; *Angew. Chem.* **2014**, *126*, 5409; b) J. Liu, Z. Fang, Q. Zhang, Q. Liu, X. Bi, *Angew. Chem. Int. Ed.* **2013**, *52*, 6953; *Angew. Chem.* **2013**, *125*, 7091; c) J. Liu, Z. Liu, N. Wu, P. Liao, X. Bi, *Chem. Eur. J.* **2014**, *20*, 2154; d) J. Liu, Z. Liu, P. Liao, X. Bi, *Org. Lett.* **2014**, *16*, 6204; e) Y. Ning, N. Wu, H. Yu, P. Liao, X. Li, X. Bi, *Org. Lett.* **2015**, *17*, 2198.
[17] S. Kim, S. H. Hong, *Adv. Synth. Catal.* **2015**, *357*, 1004.
[18] Z. Wang, X. Bi, P. Liao, X. Liu, D. Dong, *Chem. Commun.* **2013**, *49*, 1309.
[19] a) S. Pei, C. Xue, L. Hai, Y, Wu, *RSC Adv.* **2014**, *4*, 38055; b) R. Maggi, G. Bosica, S. Gherardi, C. Oro, G. Sartori, *Green Chem.* **2005**, *7*, 182; c) B. Croxtall, E. G. Hope, A. M. Stuart, *Chem. Commun.* **2003**, 2430; d) O. S. Wolfbeis, *Chem. Ber.* **1981**, *114*, 3471.
[20] a) C. He, G. Zhang, J. Ke, H. Zhang, J. T. Miller, A. J. Kropf, A. Lei, *J. Am. Chem. Soc.* **2013**, *135*, 488; b) Y. Liu, X. Yang, J. Yang, R. Song, J. Li, *Chem. Commun.* **2014**, *50*, 6906; c) H. Wang, L. Guo, X. Duan, *Chem. Commun.* **2013**, *49*, 10370; d) H. Wang, L. Guo, X. Duan, *Org. Lett.* **2013**, *15*, 5254.
[21] Y. Zhu, C. Yao, X. Zou, F. Hu, B. Liu, Y. Li, H. Yang, *Molecules* **2005**, *10*, 427, and references therein.
[22] a) T. J. Montavon, J. Li, J. R. Cabrera-Pardo, M. Mrksich, S. A. Kozmin, *Nat. Chem.* **2012**, *4*, 45; b) K. L. Rinehart, F. A. MacKellar, M. F. Grostic, E. C. Olson, R. J. Wnuk, A. R. Branfman, *J. Am. Chem. Soc.* **1971**, *93*, 4943; c) K. Matsuo, M. Kimura, T. Kinuta, N. Tarkai, K. Tanaka, *Chem. Pharm. Bull.* **1984**, *32*, 4197.
[23] V. Chudasama, R. J. Fitzmaurice, S. Caddick, *Nat. Chem.* **2010**, *2*, 592.
[24] a) B. Liu, H. Gao, Y. Yu, W. Wu, H. Jiang, *J. Org. Chem.* **2013**, *78*, 10319; b) X. Zeng, K. Ye, M. Lu, P. J. Chua, B. Tan, G. Zhong, *Org. Lett.* **2010**, *12*, 2414.
[25] a) G. Qiu, X. Qiu, J. Wu, *Adv. Synth. Catal.* **2013**, *355*, 3205; b) Z. Xia, Q. Zhu, *Org. Lett.* **2013**, *15*, 4110; c) G. Qiu, X. Qiu, J. Liu, J. Wu, *Adv. Synth. Catal.* **2013**, *355*, 2441.
[26] J. Daru, Z. Benda, Á. Póti, Z. Novák, A. Stirling, *Chem. Eur. J.* **2014**, *20*, 15395.
[27] S. Tong, Q. Wang, M. Wang, J. Zhu, *Angew. Chem. Int. Ed.* **2015**, *54*, 1293; *Angew. Chem.* **2015**, *127*, 1309.
[28] X. Creary, *Org. Lett.* **2000**, *2*, 2069.
[29] M. Liu, H. Wang, H. Zeng, C.-J. Li, *Sci. Adv.* **2015**, *1*, e1500020.
[30] M. J. Frisch, G. W. Trucks, H. B. Schlegel, G. E. Scuseria, M. A. Robb, J. R. Cheeseman, G. Scalmani, et al., Gaussian 09, Revision D.01; Gaussian, Inc.: Wallingford, CT, **2009**.
[31] The normal hydrogen electrode has been recalculated to be −4.28 V. See: D. G. Truhlar, C. J. Cramer, A. Lewis, J. A. Bumpus, *J. Chem. Educ.* **2004**, *81*, 596.
[32] CCDC 1413526 (**5a**) contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre.

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