Iron-Catalyzed Oxidative C−H Functionalization of Internal Olefins for the Synthesis of Tetrasubstituted Furans

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ⓢ *Supporting Information*

ABSTRACT: Tetrasubstituted furans were efficiently synthesized from Fe(OAc)$_2$-catalyzed C−H/C−H cross-dehydrogenative-coupling (CDC) reactions of activated carbonyl methylenes with *S,S*-functionalized internal olefins, that is, α-oxo ketene dithioacetals and analogues, under oxidative conditions. β-Ketoesters, 1,3-dicarbonyls, β-keto nitrile, and amide derivatives were used as the coupling partners.

The resultant alkylthio- and carbonyl-functionalized furans could be further transformed to diverse arylated furan derivatives and furan-fused *N*-heterocycles, respectively. The control experiments have revealed a radical reaction pathway.
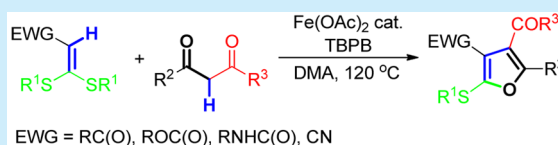
The furan motif is an important structural unit abundant in many biologically active natural products, pharmaceuticals, and agrochemicals.[1] Continuous efforts have been devoted to the synthesis of functionalized furans and furan-based complex molecules.[2] In this regard, substituted furans have usually been synthesized by means of the cyclization of alkynyl- or allenyl-bearing carbonyl compounds or through reactions between alkynes and carbonyl compounds. Thus, transition-metal-catalyzed dehydrogenative heterocyclization of 2- and 3-alkynyl enones was employed to access furan-fused carbocycles or polysubstituted furans.[3,4] Iodocyclization was also applied for this purpose.[5] Intramolecular cyclization of propargylic alcohols afforded polysubstituted furans.[6a,b] Alkynyl epoxides,[7] allenyl ketones,[8a] allenyl or homopropargylic alcohols,[8b] and allene-1,3-dicarboxylic esters[8c] can be used for the same purpose. Copper-catalyzed heterocyclization of alkynyl ketones and imines[8d] and phosphine-mediated reductive condensation of γ-acyloxybutynoates[8e] readily yielded furan derivatives.[4a] Brønsted acid catalyzed cyclization of 1,4-diketones also gave furans.[9] Transition-metal-catalyzed vinylic C−H activation/[4 + 2] *O*-annulation of α-aryl enones[10a] and oxidative cross-coupling of 1,3-dicarbonyl compounds or β-ketoesters[10b] with internal alkynes formed functionalized furans. α-Diazocarbonyls[11a] and *N*-tosylhydrazones[11b] were used for metalloradical cyclization with alkynes to construct polysubstituted furans. The combination of *N*-arylimines and alkynylbenziodoxolones was utilized for the synthesis of polysubstituted furans.[12] A two-step reaction procedure of aldehydes with propargylic alcohols was developed to prepare highly substituted furans.[13]

Due to the ready C−H addition to olefinic C=C bonds to form dihydrofurans,[14] only a limited number of olefins have been documented for the synthesis of polysubstituted furans. Fused furans and naphthofurans were synthesized through a copper/P(*t*Bu)$_3$-mediated oxidative radical [3 + 2] cyclization between olefins or alkynes and cyclic ketones,[15a] and the same type of reactions occurred between styrenes and aryl alkyl ketones.[15b] Photocatalytic reactions of styrenes and α-chloroalkyl ketones afforded polysubstituted furans.[15c] Manganese dioxide promoted the oxidative cyclization of enones with 1,3-dicarbonyl compounds to give 3,4-dicarbonyl-substituted furans.[15d] In order to avoid formation of dihydrofurans, functionalized olefins were usually reacted with carbonyl compounds. Using such a synthetic strategy, 2-siloxy-1-olefins,[16a] *gem*-difluoro olefins,[16b] β-nitrostyrenes,[16c] enamines,[16d] 2,3-dibromo-1-propenes,[16e] and α,β-unsaturated carboxylic acids[16f] have been reported for substituted furan synthesis. Palladium-catalyzed intramolecular oxidative cycloisomerization of 2-cinnamyl-1,3-dicarbonyls was also applied to synthesize furan derivatives.[17]

Although a variety of methods have been developed for furan synthesis, more diverse and environmentally benign procedures are strongly desired to access highly functionalized furans. In this context, C−H/C−H cross-dehydrogenative-coupling (CDC) reactions[18] are attractive for the establishment of a furan backbone. Gold-catalyzed alkynylation of 1,3-dicarbonyl compounds with terminal alkynes efficiently proceeded to afford 3-alkynylfurans.[19a] Stoichiometric Ag$_2$CO$_3$ mediated the same reactions to give 1,2,4-trisubstituted furans.[19b] Molecular iodine effected the oxidative cross-coupling of β-ketoesters and terminal alkynes to generate furan derivatives.[19c] During the ongoing investigation of internal olefinic C−H activation,[20] we were encouraged by FeCl$_3$·H$_2$O-catalyzed benzofuran synthesis from the arene C(sp^2)−H/C(sp^3)−H CDC reactions of phenols and β-keto esters[21] and the merits of iron catalysis[22]

and reasonably envisioned that α-oxo ketene dithioacetals,[23] a class of functionalized internal olefins, might be used for the synthesis of highly functionalized furans through direct olefinic C(sp^2)–H functionalization with the C(sp^3)–H bond of a suitable carbonyl compound. Herein, we disclose Fe(OAc)$_2$-catalyzed oxidative annulations of α-oxo ketene dithioacetals with β-ketoesters and related compounds for the synthesis of tetrasubstituted furans.

Initially, the reaction of α-benzoyl ketene di(methylthio)-acetal (**1a**) with ethyl acetoacetate (**2a**) was conducted to optimize the reaction conditions (eq 1) (see the Supporting
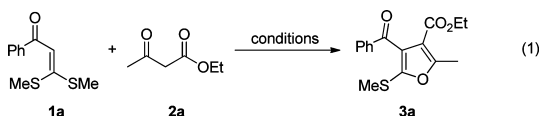
Information for details). With 2 mol % of FeCl$_3$ as the catalyst and 3 equiv of *tert*-butyl peroxybenzoate (TBPB) as the oxidant, the reaction of **1a** and **2a** in a 1:3 molar ratio proceeded in *N,N*-dimethylacetamide (DMA) at 120 °C for 15 h under an argon atmosphere, forming the target product, that is, tetrasubstituted furan **3a**, in 40% yield. Use of Fe(OAc)$_2$ as the catalyst remarkably enhanced the yield to 83%. Increasing the loading of TBPB to 4 equiv or using 5 mol % of the catalyst did not improve the reaction efficiency, and use of a smaller amount of the oxidant or catalyst deteriorated the product yield. Both di-*tert*-butylperoxide (DTBP) and *tert*-butyl hydro-peroxide (TBHP) were not effective oxidants. Elevating the reaction temperature to 130 °C did not enhance the yield either. Extending the reaction time to 20 h improved the formation of **3a** (87%), which was thus isolated in 79% yield. Under an air or oxygen atmosphere, the product yield was lessened to 70–75%. Without the catalyst or oxidant, the desired reaction could not efficiently proceed to form **3a** (35%) or did not occur.

Under the optimized conditions, the scope of α-oxo ketene dithioacetals (**1**) was explored (Scheme 1). The analogues of **1a**, that is, substituted α-benzoyl ketene dithioacetals, exhibited various reactivities to form the target furan products of type **3** in good to excellent yields. No obvious steric effects were observed for the methyl and methoxy-substituted α-benzoyl ketene dithioacetal substrates, and their reactions with **2a** afforded products **3b–f** (75–84%). The steric/electronic effects were obvious among the halo-substituted α-benzoyl-bearing substrates. *m*-Cl (F)- and *p*-Br (F)-substituted substrates reacted with **2a** to give the corresponding products **3g** and **3i–k** in 60–61% yields, while *p*-Cl-benzoyl-bearing substrate reacted more efficiently to yield furan **3h** (78%), even reaching 75% yield from a 2 mmol scale reaction (see the SI). 4-Trifluoromethyl demonstrated an obvious negative electronic impact on the yield of **3l** (62%). The bulky α-naphthoyl moiety exhibited a steric effect to render the formation of **3m** in 65% yield. α-Heteroaroyl ketene dithioacetals smoothly underwent the reaction to generate **3n–p** (50–70%), exhibiting various reactivities due to the different aromaticities of the *O*-, *S*-, and *N*-heteroaryl functionalities. α-Acetyl ketene di(methylthio)-acetal exhibited a good reactivity to afford **3q** (75%), whereas a steric effect was observed in the case of using α-cyclo-propylcarbonyl substrate, leading to the target product **3r** in 50% yield. Treatment of α-ester, amide, and cyano ketene dithioacetals with **2a** under the standard conditions could give the target products **3s–u** (40–66%), respectively, demonstrat-
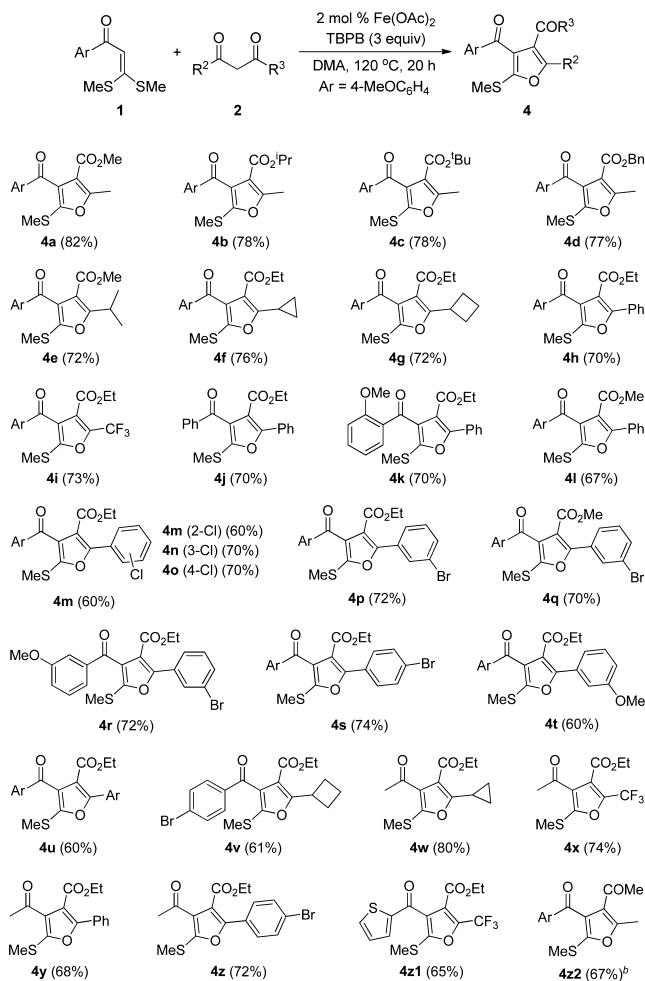
Scheme 1. Scope of Ketene Dithioacetals 1[a]
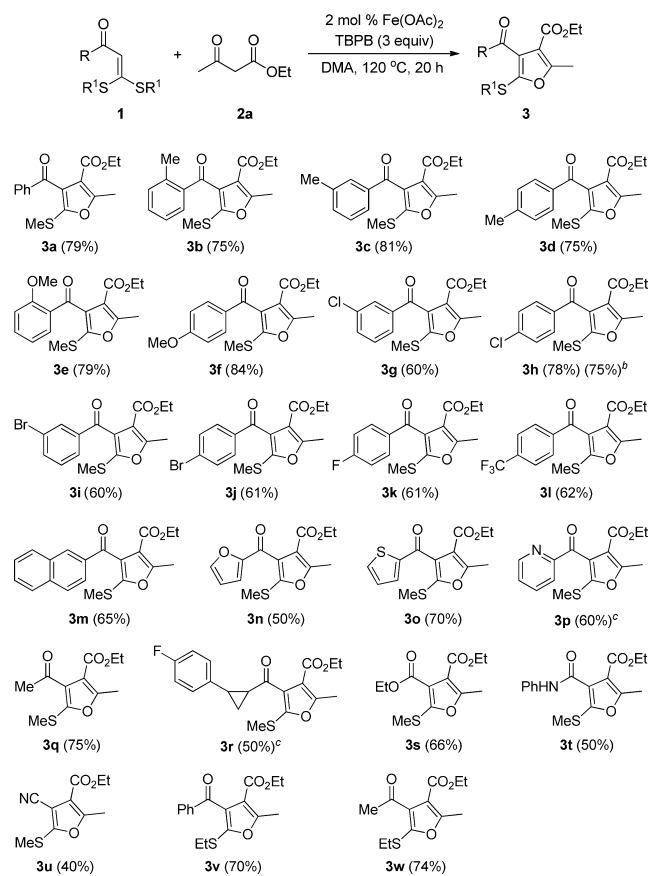
[a]Conditions: **1** (0.5 mmol), **2a** (1.5 mmol), Fe(OAc)$_2$ (0.01 mmol), TBPB (1.5 mmol), DMA (2.0 mL), 120 °C, 0.1 MPa argon, 20 h. Yields refer to the isolated products. [b]**1h** (2.0 mmol), **2a** (6.0 mmol), Fe(OAc)$_2$ (0.04 mmol), TBPB (6.0 mmol), DMA (5.0 mL). [c]48 h.

ing a good diversity of the present synthetic methodology. α-Oxo ketene di(ethylthio)acetals also efficiently reacted with **2a** to form the target products **3v** (70%) and **3w** (74%). It is clear that the internal olefin substrates are widely substituent tolerant.

Next, the protocol generality was investigated by performing the reactions of α-oxo ketene dithioacetals **1** with a variety of β-ketoesters **2** (Scheme 2). Under the standard conditions, the reaction of α-(4-methoxybenzoyl) ketene di(methylthio)acetal (**1f**) reacted with methyl acetoacetate (**2b**) to yield the target furan product **4a** (82%), exhibiting a reactivity similar to that of ethyl acetoacetate (**2a**) as compared to the formation of **3f** (84%) (Scheme 1). Variation of the alkyl moieties to isopropyl, *tert*-butyl, and benzyl in acetoacetates **2c–e** did not obviously alter the reaction efficiency, leading to furans **4b–d** (77–78%). However, when the the bulkiness of the β-ketoester substrates was increased, the product yields were dropped from 84% for **3f** to 70–76% for **4e–h**. It should be noted that 4,4,4-trifluoroacetoacetate (**2j**) also exhibited a decent reactivity to produce **4i** (73%). In the case of using unsubstituted ethyl (or methyl) 3-oxo-3-phenylpropanoates, the steric effect from the substituted α-benzoyl moieties was not obvious, resulting in **4j–l** in 67–70% yields. However, ethyl 3-oxo-3-(2′-chlorophenyl)propanoate (**2l**) showed an obvious steric effect to deteriorate the product yield to 60% for **4m**, and *m*- or *p*-halo-substituted phenyl groups did not exhibit obvious steric/

Scheme 2. Scope of β-Ketoesters 2[a]

electronic effects on the reaction efficiency to render the formation of **4n–s** (70–74%). 3- and 4-methoxy substituents on the aryl moiety of β-ketoesters and a 4-bromo substituent on the benzoyl moiety of an α-oxo ketene dithioacetal lessened the substrate reactivity to form **4t–v** (60–61%). α-Acetyl ketene di(methylthio)acetal also exhibited a decent reactivity to interact with various β-ketoesters to give **4w–z** (68–80%). α-(Thiophene-2-carbonyl) ketene di(methylthio)acetal reacted with 4,4,4-trifluoroacetoacetate to form **4z1** in 65% yield. It is noteworthy that internal olefin **1f** reacted with the 1,3-dicarbonyl compound, that is, acetoacetone, under the standard conditions to afford 3,4-dicarbonyl-tetrasubstituted furan **4z2** (67%). The molecular structures of compounds **3** and **4** were further confirmed by the X-ray single-crystal structural determination of compound **4j** (see the SI).

In contrast to most of the known substituted furans, the present tetrasubstituted furans **3** and **4** bear three readily convertible functional groups, i.e., alkylthio, carbonyl, and ester, at the 2-, 3-, and 4-positions of the furan backbone. This structural feature is highly desired for furans to be used as organic synthons. Thus, derivation of furans **3** and **4** was conducted by palladium-catalyzed Liebeskind–Srogl cross-coupling reactions with arylboronic acids and condensation

with hydrazine (Scheme 3). With benzeneboronic acid and its 4-chloro, 4- and 2-methoxy, and 3-methyl-substituted ana-

Scheme 3. Derivation of Furans 3 and 4[a]
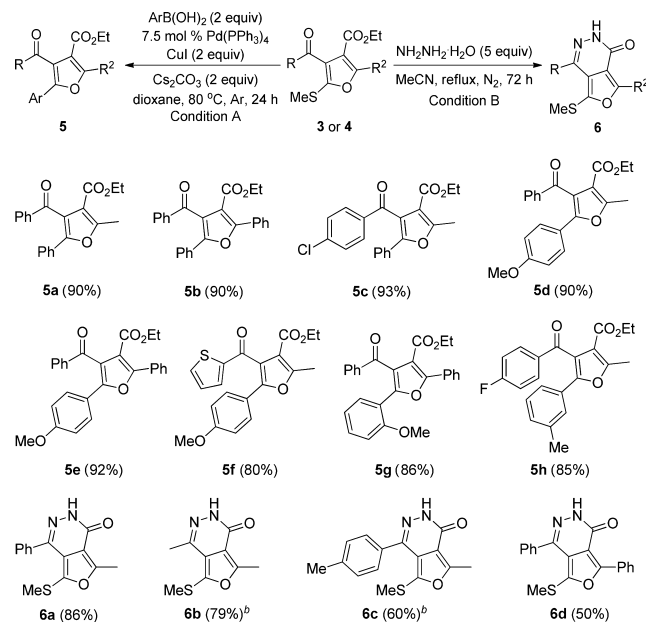
logues, 2-arylated tetrasubstituted furans **5a–h** were efficiently obtained (80–93%). The condensation reactions afforded potentially bioactive furan-fused pyridazinone derivatives[24] **6a–d** in 50–86% yields.

To probe into the reaction mechanism addition of 3 equiv of a radical scavenger such as 2,2,6,6-tetramethyl-1-piperidinyloxy or 2,6-di-*tert*-butyl-4-methylphenol to the reaction mixture of **1a** with **2a** completely inhibited the reaction, suggesting a radical pathway involved in the reaction.[22] The kinetic isotope effect experiments were explored by conducting the reactions of **1a** and its deuterated form **1a**[D][20e] with **2a** under the standard conditions, respectively. A secondary isotope effect[25] was observed with $k_H/k_D = 1.1$, which indicates that cleavage of the internal olefinic C–H bond in **1a** is not involved in the rate-determining step of the overall catalytic cycle. On the basis of these results and the literature reports,[26] a plausible radical oxidative reaction mechanism is proposed (see the SI for details).

In summary, efficient iron-catalyzed direct regioselective radical oxidative annulation of *S,S*-functionalized internal olefins with β-ketoesters and analogues has been realized to synthesize tetrasubstituted furans. The highly functionalized furan products can be readily transformed to 2-arylfurans and 2,3-furan-fused pyridazinones through catalytic C–S cleavage and condensation with hydrazine, respectively. The present protocol provides a concise and environmentally benign route to highly functionalized furan derivatives.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.orglett.7b01431.

> Experimental materials and procedures, NMR of compounds, and X-ray crystallographic analysis for compound **4j** (PDF)
> X-ray crystallographic data for compound **4j**(CIF)

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Notes

The authors declare no competing financial interest.

■ REFERENCES

(1) Hasegawa, F.; Niidome, K.; Migihashi, C.; Murata, M.; Negoro, T.; Matsumoto, T.; Kato, K.; Fujii, A. *Bioorg. Med. Chem. Lett.* **2014**, *24*, 4266.

(2) Kalaitzakis, D.; Triantafyllakis, M.; Ioannou, G. I.; Vassilikogiannakis, G. *Angew. Chem., Int. Ed.* **2017**, *56*, 4020. (b) Hao, H. D.; Trauner, D. *J. Am. Chem. Soc.* **2017**, *139*, 4117.

(3) (a) Zhou, L.; Zhang, M.; Li, W.; Zhang, J. L. *Angew. Chem., Int. Ed.* **2014**, *53*, 6542. (b) Chen, Z.-W.; Luo, M.-T.; Ye, D.-N.; Zhou, Z.-G.; Ye, M.; Liu, L.-X. *Synth. Commun.* **2014**, *44*, 1825.

(4) (a) Yao, Q.; Liao, Y.; Lin, L.; Lin, X. B.; Ji, J.; Liu, X. H.; Feng, X. M. *Angew. Chem., Int. Ed.* **2016**, *55*, 1859. (b) Yang, J. M.; Li, Z. Q.; Li, M. L.; He, Q.; Zhu, S. F.; Zhou, Q. L. *J. Am. Chem. Soc.* **2017**, *139*, 3784. (c) Xiao, Y.; Zhang, J. L. *Angew. Chem., Int. Ed.* **2008**, *47*, 1903. (d) Pathipati, S. R.; van der Werf, A.; Eriksson, L.; Selander, N. *Angew. Chem., Int. Ed.* **2016**, *55*, 11863.

(5) Cho, C. H.; Shi, F.; Jung, D. I.; Neuenswander, B.; Lushington, G. H.; Larock, R. C. *ACS Comb. Sci.* **2012**, *14*, 403.

(6) (a) Morcillo, S. P.; Leboeuf, D.; Bour, C.; Gandon, V. *Chem. - Eur. J.* **2016**, *22*, 16974. (b) Yoshida, M.; Ohno, S.; Shishido, K. *Chem. - Eur. J.* **2012**, *18*, 1604.

(7) (a) Wang, T.; Wang, C. H.; Zhang, J. L. *Chem. Commun.* **2011**, *47*, 5578. (b) Blanc, A.; Tenbrink, K.; Weibel, J. M.; Pale, P. *J. Org. Chem.* **2009**, *74*, 5342. (c) McDonald, M.; Schultz, C. C. *J. Am. Chem. Soc.* **1994**, *116*, 9363.

(8) (a) Dudnik, A. S.; Gevorgyan, V. *Angew. Chem., Int. Ed.* **2007**, *46*, 5195. (b) Peng, L. L.; Zhang, X.; Ma, M.; Wang, J. B. *Angew. Chem., Int. Ed.* **2007**, *46*, 1905. (c) Li, H. L.; Wang, Y.; Sun, P. P.; Luo, X. Y.; Shen, Z. L.; Deng, W. P. *Chem. - Eur. J.* **2016**, *22*, 9348. (d) Dudnik, A. S.; Sromek, A. W.; Rubina, M.; Kim, J. T.; Kel'i, A. V.; Gevorgyan, V. *J. Am. Chem. Soc.* **2008**, *130*, 1440. (e) Jung, C.-K.; Wang, J.-C.; Krische, M. J. *J. Am. Chem. Soc.* **2004**, *126*, 4118.

(9) (a) Amarnath, V.; Amarnath, K. *J. Org. Chem.* **1995**, *60*, 301. (b) Mao, S.; Zhu, X.-Q.; Gao, Y.-R.; Guo, D.-D.; Wang, Y.-Q. *Chem. - Eur. J.* **2015**, *21*, 11335.

(10) (a) Zhao, Y. S.; Li, S. Q.; Zheng, X. S.; Tang, J. B.; She, Z. J.; Gao, G.; You, J. S. *Angew. Chem., Int. Ed.* **2017**, *56*, 4286. (b) Roslan, I. I.; Sun, J.; Chuah, G.-K.; Jaenicke, S. *Adv. Synth. Catal.* **2015**, *357*, 719.

(11) (a) Cui, X.; Xu, X.; Wojtas, L.; Kim, M. M.; Zhang, X. P. *J. Am. Chem. Soc.* **2012**, *134*, 19981. (b) Huang, Y. B.; Li, X. W.; Yu, Y.; Zhu, C. L.; Wu, W. Q.; Jiang, H. F. *J. Org. Chem.* **2016**, *81*, 5014.

(12) Lu, B. L.; Wu, J. L.; Yoshikai, N. *J. Am. Chem. Soc.* **2014**, *136*, 11598.

(13) Lenden, P.; Entwistle, D. A.; Willis, M. C. *Angew. Chem., Int. Ed.* **2011**, *50*, 10657.

(14) Tang, S.; Liu, K.; Long, Y.; Gao, X. L.; Gao, M.; Lei, A. W. *Org. Lett.* **2015**, *17*, 2404.

(15) (a) Naveen, Y.; Deb, A.; Maiti, D. *Angew. Chem., Int. Ed.* **2017**, *56*, 1111. (b) Dey, A.; Ali, M. A.; Jana, S.; Hajra, A. *J. Org. Chem.* **2017**, *82*, 4812. (c) Wang, S.; Jia, W.-L.; Wang, L.; Liu, Q.; Wu, L.-Z. *Chem. - Eur. J.* **2016**, *22*, 13794. (d) Yue, Y. Y.; Zhang, Y. L.; Song, W. W.; Zhang, X.; Liu, J. M.; Zhuo, K. L. *Adv. Synth. Catal.* **2014**, *356*, 2459.

(16) (a) Tan, W. W.; Yoshikai, N. *J. Org. Chem.* **2016**, *81*, 5566. (b) Zhang, X.; Dai, W.; Wu, W.; Cao, S. *Org. Lett.* **2015**, *17*, 2708. (c) Ghosh, M.; Mishra, S.; Hajra, A. *J. Org. Chem.* **2015**, *80*, 5364. (d) Jiang, Y.; Khong, V. Z. Y.; Lourdusamy, E.; Park, C.-M. *Chem. Commun.* **2012**, *48*, 3133. (e) Schmidt, D.; Malakar, C. C.; Beifuss, U. *Org. Lett.* **2014**, *16*, 4862. (f) Yang, Y.; Yao, J.; Zhang, Y. H. *Org. Lett.* **2013**, *15*, 3206.

(17) Nallagonda, R.; Reddy, R. R.; Ghorai, P. *Chem. - Eur. J.* **2015**, *21*, 14732.

(18) (a) Girard, S. A.; Knauber, T.; Li, C.-J. *Angew. Chem., Int. Ed.* **2014**, *53*, 74. (b) Liu, C.; Yuan, J.; Gao, M.; Tang, S.; Li, W.; Shi, R.; Lei, A. W. *Chem. Rev.* **2015**, *115*, 12138. (c) Gensch, T.; Hopkinson, M. N.; Glorius, F.; Wencel-Delord, J. *Chem. Soc. Rev.* **2016**, *45*, 2900.

(19) (a) Ma, Y. H.; Zhang, S.; Yang, S. P.; Song, F. J.; You, J. S. *Angew. Chem., Int. Ed.* **2014**, *53*, 7870. (b) He, C.; Guo, S.; Ke, J.; Hao, J.; Xu, H.; Chen, H. Y.; Lei, A. W. *J. Am. Chem. Soc.* **2012**, *134*, 5766. (c) Tang, S.; Liu, K.; Long, Y.; Qi, X. T.; Lan, Y.; Lei, A. W. *Chem. Commun.* **2015**, *51*, 8769.

(20) (a) Jiang, Q. B.; Guo, T. L.; Wu, K. K.; Yu, Z. K. *Chem. Commun.* **2016**, *52*, 2913. (b) Yang, X. G.; Liu, Z. Q.; Sun, C. L.; Chen, J. P.; Yu, Z. K. *Chem. - Eur. J.* **2015**, *21*, 14085. (c) Yang, Q.; Wu, P.; Chen, J. P.; Yu, Z. K. *Chem. Commun.* **2014**, *50*, 6337. (d) Jin, W. W.; Yang, Q.; Wu, P.; Chen, J. P.; Yu, Z. K. *Adv. Synth. Catal.* **2014**, *356*, 2097. (e) Mao, Z. F.; Huang, F.; Yu, H. F.; Chen, J. P.; Yu, Z. K.; Xu, Z. Q. *Chem. - Eur. J.* **2014**, *20*, 3439. (f) Yu, H. F.; Jin, W. W.; Sun, C. L.; Chen, J. P.; Du, W. M.; He, S. B.; Yu, Z. K. *Angew. Chem., Int. Ed.* **2010**, *49*, 5792. (g) Yu, H. F.; Yu, Z. K. *Angew. Chem., Int. Ed.* **2009**, *48*, 2929.

(21) Guo, X. W.; Yu, R.; Li, H. J.; Li, Z. P. *J. Am. Chem. Soc.* **2009**, *131*, 17387.

(22) (a) Yang, X.-H.; Song, R.-J.; Xie, Y.-X.; Li, J.-H. *ChemCatChem* **2016**, *8*, 2429. (b) Lv, L. Y.; Li, Z. P. *Top. Curr. Chem.* **2016**, *374*, 38. (c) Cera, G.; Ackermann, L. *Top. Curr. Chem.* **2016**, *374*, 57. (d) Sun, C. L.; Li, B. J.; Shi, Z. J. *Chem. Rev.* **2011**, *111*, 1293.

(23) (a) Wang, L. D.; He, W.; Yu, Z. K. *Chem. Soc. Rev.* **2013**, *42*, 599. (b) Pan, L.; Bi, X. H.; Liu, Q. *Chem. Soc. Rev.* **2013**, *42*, 1251.

(24) (a) Singh, J.; Sharma, D.; Bansal, R. *Future Med. Chem.* **2017**, *9*, 95. (b) Saini, M.; Mehta, D. K.; Das, R.; Saini, G. *Mini-Rev. Med. Chem.* **2016**, *16*, 996.

(25) Halevi, E. A. *Prog. Phys. Org. Chem.* **1963**, *1*, 109.

(26) (a) Lv, L. Y.; Li, Z. P. *Chin. J. Chem.* **2017**, *35*, 303. (b) Bai, X. H.; Lv, L. Y.; Li, Z. P. *Org. Chem. Front.* **2016**, *3*, 804. (c) Lv, L. Y.; Li, Z. P. *Org. Lett.* **2016**, *18*, 2264. (d) Lv, L. Y.; Xi, H.; Bai, X. H.; Li, Z. P. *Org. Lett.* **2015**, *17*, 4324. (e) Lv, L. Y.; Lu, S. L.; Guo, Q. X.; Shen, B. J.; Li, Z. P. *J. Org. Chem.* **2015**, *80*, 698.