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Ligand-free copper-catalyzed C(sp^3)–H imidation of aromatic and aliphatic methyl sulfides with *N*-fluorobenzenesulfonimide†

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A novel and efficient process has been developed for copper-catalyzed C(sp^3)–H direct imidation of methyl sulfides with *N*-fluorobenzenesulfonimide(NFSI). Without using any ligands, various methyl sulfides including aromatic and aliphatic methyl sulfides, can be transformed to the corresponding *N*-((phenylthio)methyl)-benzenesulfonamide derivatives in good to excellent yields.

Nitrogen-containing molecules are widely present in natural products, drug molecules, agrochemicals, and other chemical materials.[1] Among the large number of approaches developed for their synthesis,[2] the pathway through C–N bond formation has been of great interest to synthetic chemists. This is mainly due to the fact that the introduction of amino groups can facilitate the tuning of physicochemical properties of the molecules leading to biologically significant structures(Fig. 1).[3] Typical methods for C–N bond formation include Buchwald–Hartwig, Ullmann–Goldberg and Chan–Evans–Lam imidations, which are mostly transition metal catalyzed, and require pre-functionalization of starting materials.[4] Recently, a more concise and atom-economic alternative to such imidations has been investigated by direct C–H imidation of oxidized nitrogen reagents and carbon nucleophiles. This process is also transition metal-catalyzed, however avoids prefunctionalization of coupling partners, thus providing a more efficient and environmentally friendly approach for C–N bond formation.[5,6] However, the requirements of directing groups and a stoichiometric amount of oxidants have limited the wide application of these C–H imidation processes.

N-Fluorobenzenesulfonimide (NFSI), a commonly used fluorination reagent and nitrogen source,[7–16] has been recently employed in a variety of aminative functionalization reactions, such as imidations of aromatic C–H bond,[8] alkenes or unsaturated ketones,[9] alkyne[10] and benzylic or allylic C–H bond.[11–16] Various transition metals have been explored to catalyze direct imidation of C(sp^3)–H bonds with NFSI (Scheme 1). In 2010, a pioneering work on remote amide-directed palladium-catalyzed intermolecular highly selective benzylic C–H imidation with *N*-fluorobenzenesulfonimide was disclosed by Zhang's group.[11] Liu's[12] group proposed a copper-catalyzed C(sp^3)–H imidation strategy for synthesizing various benzylic amines from benzylic hydrocarbons. The first biocompatible iron-catalyzed benzylic C(sp^3)–H imidation of methylarenes with NFSI have been achieved by Bao *et al.* (Scheme 1a).[13] Using palladium as catalyst has also been reported by Muñiz *et al.*[14] to catalyze intermolecular sequence consisting of the C–H activation, where amidation of methyl groups relied on NFSI as both oxidant and nitrogen sources. In addition, copper-catalyzed amidation of 8-methylquinolines with *N*-fluoroarylsulfonimides *via* C(sp^3)–H activation has been examined by Zheng *et al.* (Scheme 1b).[15] Furthermore, copper-catalyzed sequential C(sp^2)/C(sp^3)–H imidation of 2-vinylanilines has been performed with NFSI for the efficient synthesis of indole frameworks (Scheme 1c).[16]

Despite considerable progress in studying transition metal catalyzed C(sp^3)–H imidation reactions, limited effort has been made in the methyl C(sp^3)–H imidation of thioanisoles with NFSI. Xu and co-workers[17] reported the direct imidation of the methyl C(sp^3)–H bond of thioanisoles. However, the scope of substrates was limited to thioaromatics with low product yields. Recently, our group has developed a novel method for copper-catalyzed direct imidation of thiophene with NFSI, demonstrating a convenient and complementary approach to

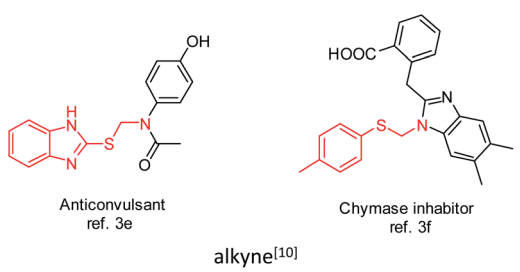

Fig. 1 Representative examples of bioactive amides.

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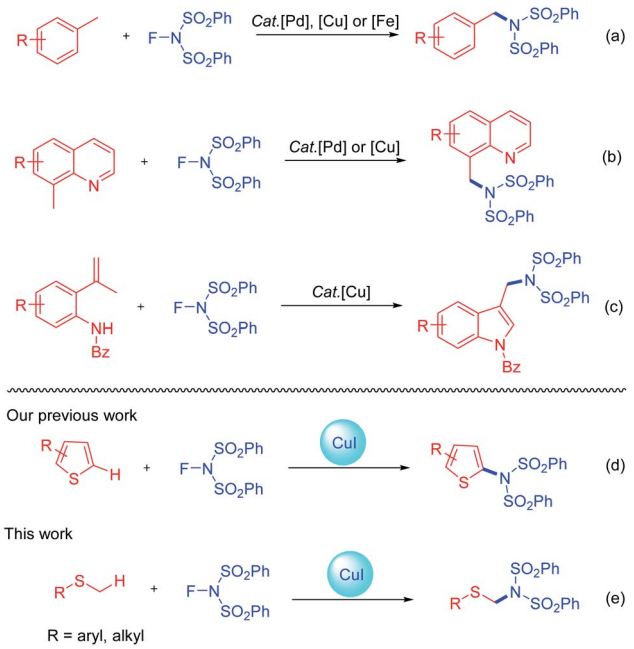
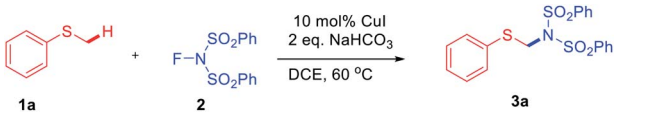


Scheme 1 Methodologies for C(sp^3)–H imidation using NFSI.

synthesizing the *gem*-thiazamethylene structural motifs exist in biologically active structures (Scheme 1d).[8h] Built on this development, the present study was extended to the direct C(sp^3)–H imidation of methyl sulfides with NFSI catalyzed with ligand-free copper catalysts (Scheme 1e), where both aromatic and aliphatic methyl sulfides were investigated. This strategy provides a facile and efficient process for transition metal-catalyzed C(sp^3)–H direct imidation of methyl sulfides.

Initially, the reaction of methyl(phenyl)sulfane **1a** with NFSI was carried out successfully by using CuI as a catalyst and $NaHCO_3$ as a base. In the presence of 10 mol% CuI and 2 equiv. of $NaHCO_3$, **1a** and with NFSI were under stirring in a reaction medium of 1,2-dichloroethane (DCE) at room temperature for 8 h, and the desired product **3a** was obtained in 55% yield (Table 1, entry 1). A brief eximidation of the temperature effect revealed that a temperature of 60 °C gave the highest yield of **3a**, *i.e.* 85% (Table 1, entries 2–4). A higher temperatures of 100 °C showed unfavorable effect on the product yield (Table 1, entry 5). By further examining more copper catalysts including CuCl, CuBr and CuOAc, no higher yields were observed (Table 1, entries 6–8). In the absence of copper catalyst, a 49% product yield was obtained (Table 1, entry 9). Different bases were also employed where $NaHCO_3$ was found to be the most suitable under identical conditions in the reaction process (Table 1, entries 3 and 10–13). In the absence of a base, no detectable product **3a** was obtained which indicated a crucial role that the base played in the reaction (Table 1, entry 14). The effect of solvent was then investigated with a range of solvents for this reaction including acetonitrile (CH_3CN), dichloromethane (DCM), dimethyl sulfoxide (DMSO) and *N*,*N*-dimethylformamide (DMF). It was found that, interestingly, the reaction proceeded in both CH_3CN and DCM whereas the use of DMSO and DMF failed to give the desired product (Table 1, entries 15–18).

Table 1 Optimization of the reaction conditions[a,b]

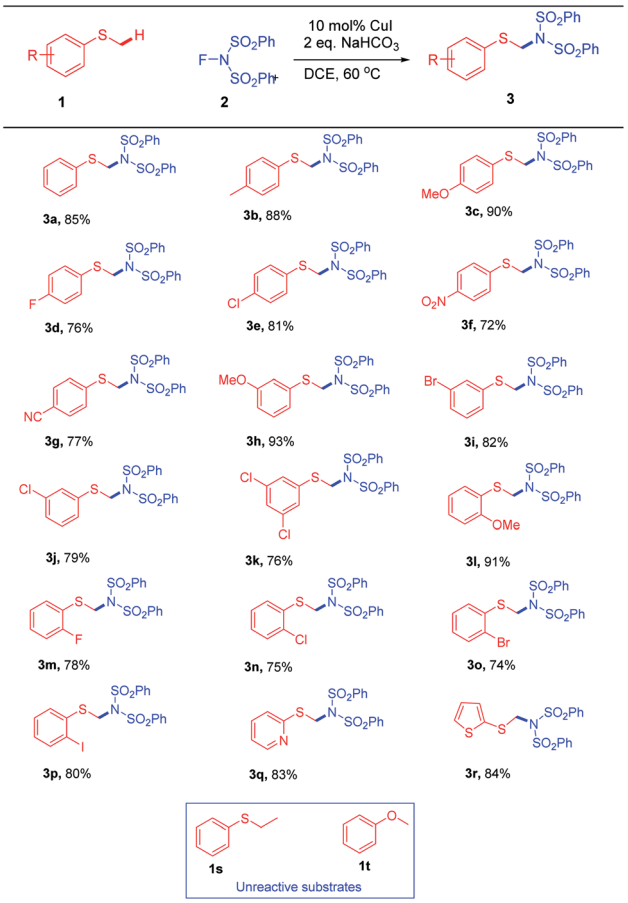


Entry	Catalyst	Base (2 equiv.)	Solvent	Temperature (°C)	Yield [b](%)
1	CuI	$NaHCO_3$	DCE	25	55
2	CuI	$NaHCO_3$	DCE	40	76
3	CuI	$NaHCO_3$	DCE	60	85
4	CuI	$NaHCO_3$	DCE	80	81
5	CuI	$NaHCO_3$	DCE	100	73
6	CuCl	$NaHCO_3$	DCE	60	76
7	CuBr	$NaHCO_3$	DCE	60	80
8	CuOAc	$NaHCO_3$	DCE	60	56
9	—	$NaHCO_3$	DCE	60	49
10	CuI	Na_2CO_3	DCE	60	10
11	CuI	NaOtBu	DCE	60	15
12	CuI	K_2CO_3	DCE	60	18
13	CuI	Cs_2CO_3	DCE	60	20
14	CuI	—	DCE	60	n. r.[c]
15	CuI	$NaHCO_3$	CH_3CN	60	45
16	CuI	$NaHCO_3$	DCM	60	55
17	CuI	$NaHCO_3$	DMSO	60	n. r.[c]
18	CuI	$NaHCO_3$	DMF	60	n. r.[c]

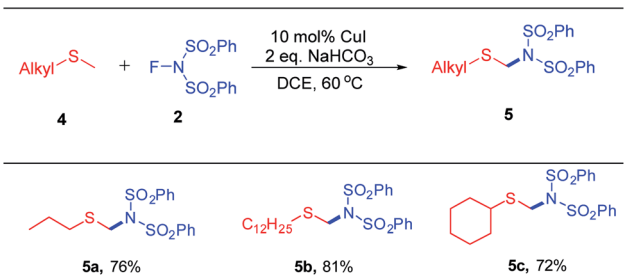
[a] Reactions were carried out on a 0.5 mmol scale in 3.0 mL of solvent with 1 equiv. of **1a**, 1.2 equiv. of **2**, 2 equiv. of base and 10 mol% of catalyst at 60 °C for 8 h. [b] Isolated yield after column chromatography. [c] n. r. = No reaction.

In summary, the optimal reaction conditions were as follows: methyl(phenyl)sulfane **1a** (0.5 mmol), NFSI (1.2 equiv.), CuCl (0.1 equiv.) and $NaHCO_3$ (2.0 equiv.) at 60 °C in DCE (3 mL) for 8 h.

By applying the optimized reaction conditions, the generality and limitations of this ligand-free C–N bond formation were further investigated. The results are presented in Scheme 2. The reaction of NFSI and a variety of methyl(phenyl)sulfane derivatives **1** afforded the desired imidation products **3** in a range of 72–93% either electron electron-donating (**1b**, **1c**) or electron-withdrawing groups (**1d–1g**) at the para-position of the benzene ring, such as methy, OMe, halogens, or CN, reacted with NFSI effectively to give the desired benzenesulfonamides **3b–3g** in moderate to good yields (72–90%). Thioanisole substrates bearing methoxyl, bromo and chloro substituents at *meta*-position of the benzene ring were found to be good candidates for the imidation, where the corresponding products (**3h–3j**) were obtained in satisfactory yields (79–93%). Interestingly, (3,5-dichlorophenyl)(methyl)sulfane also afforded target product **3k** in a good yield (76%). Substrates bearing methoxyl (**1l**) or halogen (**1m–1p**) groups at *ortho*-position of the benzene ring were also successfully imidated with high yields (**3l–3p**). Both heterocyclic substrates 2-(methylthio)pyridine (**1q**) and 2-(methylthio)thiophene (**1r**) also worked nicely to deliver the imidation products with good to excellent yields (**3q–3r**, 83–84%). Likely due to the steric effect, ethyl(phenyl)sulfane **1s** did



Scheme 2 Substrate Scope of Thioanisoles.[a,b] [a]Reactions were carried out on a 0.5 mmol scale in 3.0 mL of solvent with 1.0 equiv. of **1**, 1.2 equiv. of **2**, 2 equiv. of base and 10 mol% of catalyst at 60 °C for **8h**. [b] Isolated yield after column chromatography.

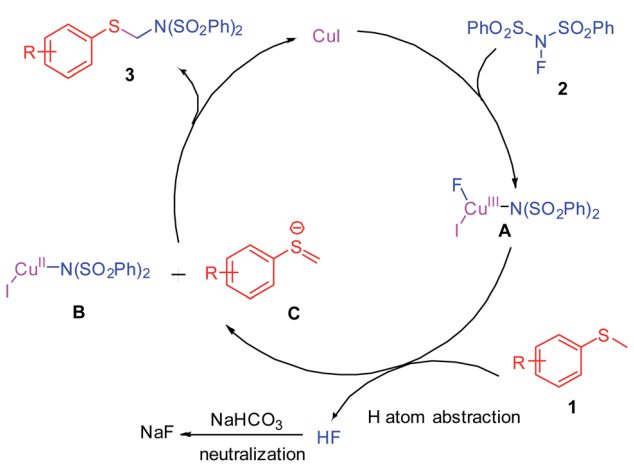


Scheme 3 Substrate scope of alkyl methyl sulfides.[a,b] [a]Reactions were carried out on a 0.5 mmol scale in 3.0 mL of solvent with 1.0 equiv. of **1**, 1.2 equiv. of **2**, 2 equiv. of base and 10 mol% of catalyst at 60 °C for **8h**. [b] Isolated yield after column chromatography.

not provide imidated product under the optimized reaction conditions. Unfortunately, largely associated with the electronic effect, anisole **1t** also failed to afford the desired product.

To further extend the scope of the imidation reaction, various alky methyl sulfides were also explored as the reactants (Scheme 3). It was demonstrated that both short chain methyl(propyl)sulfane (**4a**) and long chain dodecyl(methyl)sulfane

Scheme 4 Scaled-up study and application of **3i**.



Scheme 5 Plausible reaction pathway.

(**4b**) reacted well to afford the desired products in satisfactory yields (**5a** and **5b**). Moreover, cyclohexyl(methyl)sulfane (**4c**) smoothly participated in this reaction to give the desired imidated product in good yields (**5c**).

In order to demonstrate the synthetic utility of the reaction we developed, this imidation reaction was performed on a 7.0 mmol scale in the presence of 10 mol% of CuI catalyst, giving 2.9 g of the desired product **3i** in 83% yield under standard conditions (Scheme 4). Notably, **3i** could undergo an oxidation process in the presence of 3.0 equivalents of *m*-chloroperoxybenzoic acid (*m*-CPBA) to provide the sulfone **6** in 95% yield.

Based on the results and discussion above, a possible reaction pathway has been proposed as illustrated in Scheme 5, involving the formation of Cu(I), Cu(II), and Cu(III) complexes,[2d,17] although the exact reaction mechanism still remains to be elucidated. Initially, NFSI **2** oxidizes CuI to provide a Cu(III) species **A**. Next, the substrate **1** can attack **A** forming the key methylenethionium ions **C** and the Cu(II) species **B**. Finally, the methylenethionium ions **C** is oxidized by the Cu(II) species **B** to form the imidation product **3** and regenerate CuI for the next catalytic cycle. In this circle system, the addition of chemical equivalent base can clearly enhance increasing the product yield, where the neutralization of HF by $NaHCO_3$ is likely to accelerate the transformation from substrate **1** to intermediate **C**.

Conclusions

In conclusion, a novel and efficient process has been developed for copper-catalyzed C(sp^3)–H direct imidation of methyl sulfides with NFSI. Various methyl sulfides, including aromatic

and aliphatic methyl sulfides, can be transformed to the corresponding *N*-((phenylthio)methyl)-benzenesulfonamide derivatives in good to excellent yields. Currently, the reaction mechanism and further applications of this imidation method are under active investigation in our laboratories.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

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Notes and references

1 (*a*) R. Hili and A. K. Yudin, *Nat. Chem. Biol.*, 2006, **2**, 284; (*b*) A. L. Harvey, *Drug Discovery Today*, 2008, **13**, 894; (*c*) D. J. Newman and G. M. Cragg, *J. Nat. Prod.*, 2012, **75**, 311; (*d*) Z.-L. Li and C. Cai, *ChemistrySelect*, 2017, **2**, 8076; (*e*) J. P. Clark, K. Feng, A. Sookezain and M. C. White, *Nat. Chem.*, 2018, **10**, 583.

2 (*a*) T. Xiong and Q. Zhang, *Chem. Soc. Rev.*, 2016, **45**, 3069; (*b*) C. E. Hendrick and Q. Wang, *J. Org. Chem.*, 2017, **82**, 839; (*c*) S. Bhunia, G. G. Pawar, S. V. Kumar, Y. Jiang and D. Ma, *Angew. Chem., Int. Ed.*, 2017, **56**, 16136; (*d*) S. Lu, L.-L. Tian, T.-W. Cui, X.-Q. Hao and M.-P. Song, *J. Org. Chem.*, 2018, **83**, 13991; (*e*) W. S. Ham, J. Hillenbrand, C. Genicot and T. Ritter, *Angew. Chem., Int. Ed.*, 2019, **58**, 532.

3 (*a*) J. E. Ney and J. P. Wolfe, *J. Am. Chem. Soc.*, 2006, **128**, 15415; (*b*) J. Bariwal and E. V. Eycken, *Chem. Soc. Rev.*, 2013, **42**, 9283; (*c*) A. K. Mailyan, J. A. Eickhoff, A. S. Minakova, P. Lu and A. Zakarian, *Chem. Rev.*, 2016, **116**, 4441; (*d*) Sushmita, T. Aggarwal, N. Shibata and A. K. Verma, *Chem. - Eur. J.*, 2019, **25**, 16063; (*e*) R. N. Tiwari, K. G. Bothara, G. S. Chhabra and S. Kulkarni, *Res. J. Pharm. Technol.*, 2010, **2**, 466; (*f*) Y. Matsumoto, S. Takeuchi and N. Hase, *PCT Int. Appl.*, 2000, WO2000003997 A1 20000127.

4 (*a*) J. F. Hartwig, *Acc. Chem. Res.*, 2008, **41**, 1534; (*b*) F. Monnier and M. Taillefer, *Angew. Chem., Int. Ed.*, 2009, **48**, 6954; (*c*) D. S. Surry and S. L. Buchwald, *Chem. Sci.*, 2011, **2**, 27; (*d*) P. Ruiz-Castillo and S. L. Buchwald, *Chem. Rev.*, 2016, **116**, 12564; (*e*) S. M. Kelly, C. Han, L. Tung and F. Gosselin, *Org. Lett.*, 2017, **19**, 3021; (*f*) W. Xu, Y. Jin, H. Liu, Y. Jiang and H. Fu, *Org. Lett.*, 2011, **13**, 1274; (*g*) Z.-Y. Ge, X.-D. Fei, T. Tang, Y.-M. Zhu and J.-K. Shen, *J. Org. Chem.*, 2012, **77**, 5736; (*h*) C. Sambiagio, S. Marsden, P. A. J. Blacker and P. C. McGowan, *Chem. Soc. Rev.*, 2014, **43**, 3525; (*i*) J. C. Vantourout, H. N. Miras, A. Isidro-Llobet, S. Sproules and A. J. B. Watson, *J. Am. Chem. Soc.*, 2017, **139**, 4769.

5 (*a*) X. Yan, X. Yang and C. Xi, *Catal. Sci. Technol.*, 2014, **4**, 4169; (*b*) C. E. Hendrick, K. J. Bitting, S. Cho and Q. Wang, *J. Am. Chem. Soc.*, 2017, **139**, 11622; (*c*) Y.-H. Chen, S. Graβl and P. Knochel, *Angew. Chem., Int. Ed.*, 2018, **57**, 1108; (*d*) Y. Segawa, T. Maekawa and K. Itami, *Angew. Chem., Int. Ed.*, 2015, **54**, 66; (*e*) K. Murakami, S. Yamada, T. Kaneda and K. Itami, *Chem. Rev.*, 2017, **117**, 9302; (*f*) P. Becker, T. Duhamel, C. J. Stein, M. Reiher and K. Muniz, *Angew. Chem., Int. Ed.*, 2017, **56**, 8004; (*g*) A. E. Bosnidou and K. Muniz, *Angew. Chem., Int. Ed.*, 2019, **58**, 7485.

6 (*a*) M.-L. Louillat and F. W. Patureau, *Chem. Soc. Rev.*, 2014, **43**, 901; (*b*) K. Shin, H. Kim and S. Chang, *Acc. Chem. Res.*, 2015, **48**, 1040; (*c*) J. Jiao, K. Murakami and K. Itami, *ACS Catal.*, 2016, **6**, 610; (*d*) H. Kim and S. Chang, *ACS Catal.*, 2016, **6**, 2341; (*e*) Y. Park, Y. Kim and S. Chang, *Chem. Rev.*, 2017, **117**, 9247.

7 For selected examples, see: (*a*) X.-Y. Yang, T. Wu, R. J. Phipps and F. D. Toste, *Chem. Rev.*, 2015, **115**, 826; (*b*) T. Liang, C. N. Neumman and T. Ritter, *Angew. Chem., Int. Ed.*, 2013, **52**, 8214; (*c*) X. Wang, Z.-J. Wu and J. Wang, *Org. Lett.*, 2016, **18**, 576; (*d*) H.-H. Peng and G.-S. Liu, *Org. Lett.*, 2011, **13**, 772; (*e*) L. Yang, Y.-H. Ma, F.-J. Song and J.-S. You, *Chem. Commun.*, 2014, **50**, 3024; (*f*) F.-H. Li, Z.-J. Cai, L. Yin, S.-Y. Wang and S.-J. Ji, *Org. Lett.*, 2017, **19**, 1662; (*g*) Y.-L. Zhu, A.-F. Wang, J.-Y. Du, B.-R. Leng, S.-J. Tu, W.-J. Hao and B. Jiang, *Chem. Commun.*, 2017, **53**, 6397; (*h*) D. S. Timofeeva, A. R. Ofial and H. Mayr, *J. Am. Chem. Soc.*, 2018, **140**, 11474; (*i*) Y. Li and Q. Zhang, *Synthesis*, 2015, **47**, 159.

8 For selected examples, see: (*a*) K. Sun, Y. Li, T. Xiong, J.-P. Zhang and Q. Zhang, *J. Am. Chem. Soc.*, 2011, **133**, 1694; (*b*) G. B. Boursalian, M.-Y. Ngai, K. N. Hojczyk and T. Ritter, *J. Am. Chem. Soc.*, 2013, **135**, 13278; (*c*) R.-J. Tang, C.-P. Luo, L. Yang and C.-J. Li, *Adv. Synth. Catal.*, 2013, **355**, 869; (*d*) Y. Wang, Z.-Y. Guo, Q. Zhang and D. Li, *Asian J. Org. Chem.*, 2016, **5**, 1438; (*e*) T. Kawakami, K. Murakami and K. Itami, *J. Am. Chem. Soc.*, 2015, **137**, 2460; (*f*) E. Ito, T. Fukushima, T. Kawakami, K. Murakami and K. Itami, *Chem*, 2017, **2**, 383; (*g*) H.-H. Liu, Y. Wang, G.-J. Deng and L. Yang, *Adv. Synth. Catal.*, 2013, **355**, 3396; (*h*) S. Wang, Z. Ni, J. Wang and Y. Pan, *Org. Lett.*, 2014, **16**, 5648; (*i*) M. Singsardar, S. Mondal, R. Sarkar and A. Hajra, *ACS Omega*, 2018, **3**, 12505.

9 For selected examples, see: (*a*) P. A. Sibbald, C. F. Rosewall and F. E. Michael, *J. Am. Chem. Soc.*, 2009, **131**, 15945; (*b*) P. A. Sibbald and F. E. Michael, *Org. Lett.*, 2009, **11**, 1147; (*c*) T. Xiong, Y. Li, L.-J. Mao and Q. Zhang, *Chem. Commun.*, 2012, **48**, 2246; (*d*) H.-W. Zhang, W.-Y. Pu, T. Xiong, K. Sun, Q. Liu and Q. Zhang, *Angew. Chem., Int. Ed.*, 2013, **52**, 2529; (*e*) H.-W. Zhang, Y.-C. Song, J.-B. Zhao, J.-P. Zhang and Q. Zhang, *Angew. Chem., Int. Ed.*, 2014, **53**, 11079; (*f*) G. Zhang, T. Xiong, Z.-N. Wang, G.-X. Xu and Q. Zhang, *Angew. Chem., Int. Ed.*, 2015, **54**, 12649; (*g*) D.-H. Wang, L.-Q. Wu, Z.-Y. Lin and G.-S. Liu, *J. Am. Chem. Soc.*, 2017,

139, 6811; (*h*) T. W. Pouambeka, G. Zhang, T. Xiong and Q. Zhang, *Org. Chem. Front.*, 2017, **4**, 1420; (*i*) D.-K. Li, T.-T. Mao, J.-B. Huang and Q. Zhu, *Chem. Commun.*, 2017, **53**, 3450; (*j*) J. Xie, Y.-W. Wang, L.-W. Qi and B. Zhang, *Org. Lett.*, 2017, **19**, 1148; (*k*) H.-W. Xiao, H.-G. Shen, L. Zhu and C.-Z. Li, *J. Am. Chem. Soc.*, 2019, **141**, 11440; (*l*) M. Iwasaki, K. Nonaka, S. Zou, K. Nakajima and Y. Nishihara, *J. Org. Chem.*, 2019, **84**, 15373.

10 (*a*) G.-F. Zheng, Y. Li, J.-J. Han, T. Xiong and Q. Zhang, *Nat. Commun.*, 2015, **6**, 7011; (*b*) G.-F. Zheng, J.-B. Zhao, Z.-Y. Li, H.-Z. Sun and Q. Zhang, *Chem. - Eur. J.*, 2016, **22**, 3513; (*c*) J.-Q. Sun, G.-F. Zheng, T. Xiong and Q. Zhang, *ACS Catal.*, 2016, **6**, 3674; (*d*) J.-Q. Sun, G.-F. Zheng, Y. Li and Q. Zhang, *Org. Lett.*, 2017, **19**, 3767; (*e*) C. R. Reddy, S. K. Prajapti and R. Ranjan, *Org. Lett.*, 2018, **20**, 3128; (*f*) S. Samanta and A. Hajra, *J. Org. Chem.*, 2018, **83**, 13157; (*g*) X.-T. Zhu, W.-L. Deng, L. Ge, X.-H. Zhang and H.-L. Bao, *J. Am. Chem. Soc.*, 2019, **141**, 548.

11 T. Xiong, Y. Li, Y. Lv and Q. Zhang, *Chem. Commun.*, 2010, **46**, 6831.

12 Z.-K. Ni, Q. Zhang, T. Xiong, J.-P. Zhang and Q. Liu, *Angew. Chem., Int. Ed.*, 2012, **51**, 1244.

13 F.-Y. Bao, Y.-H. Cao, W.-B. Liu and J.-H. Zhu, *RSC Adv.*, 2019, **9**, 27892.

14 Á. Iglesias, R. Álvarez, Á. R. de Lera and K. Muñiz, *Angew. Chem., Int. Ed.*, 2012, **51**, 2225.

15 X.-L. Zhang, R. Wu, P.-J. Jiang and Q.-Z. Zheng, *Org. Biomol. Chem.*, 2016, **14**, 4789.

16 W.-B. Cao, X.-P. Xu and S.-J. Ji, *Adv. Synth. Catal.*, 2019, **361**, 1771.

17 Z.-H. Yang, S.-Y. Yang and J.-X. Xu, *Tetrahedron*, 2017, **73**, 3240.