

Cite this: *Chem. Sci.*, 2022, 13, 9056

All publication charges for this article have been paid for by the Royal Society of Chemistry

Received 19th April 2022
Accepted 30th June 2022

DOI: 10.1039/d2sc02210a

rsc.li/chemical-science

Selective desaturation of amides: a direct approach to enamides†

Xinwei Li,^{‡a} Zengrui Cheng,^{‡a} Jianzhong Liu,^a Ziyao Zhang,^a Song Song^{ID} *^a and Ning Jiao^{ID} *^{ab}

C(sp³)-H bond desaturation has been an attractive strategy in organic synthesis. Enamides are important structural fragments in pharmaceuticals and versatile synthons in organic synthesis. However, the dehydrogenation of amides usually occurs on the acyl side benefitting from enolate chemistry like the desaturation of ketones and esters. Herein, we demonstrate an Fe-assisted regioselective oxidative desaturation of amides, which provides an efficient approach to enamides and β -halogenated enamides.

Introduction

The enamide is a vital functional group in pharmaceuticals featuring excellent biological and physiological properties (Fig. 1).¹ Moreover, enamide compounds are also important and versatile synthons in organic synthesis.² Thus, the synthesis of enamides has attracted great interest from chemists for several decades.³ Recently, selective C(sp³)-H bond desaturation has been widely used in organic synthesis, including oxidative desaturation,⁴ transition-metal catalyzed desaturation,⁵ photochemical desaturation⁶ and electrochemical desaturation.⁷ However, compared to the dehydrogenation reaction of carbonyl compounds,^{7a,b,e,g,8} such as ketones,⁹ the regioselective dehydrogenation of *N*-alkanoylamides on the *N*-alkyl side with higher C-H bond dissociation energy (BDE)¹⁰ is still a tremendous challenge (Scheme 1a). Generally, the desaturation of esters¹¹ and amides¹² on the acyl side is much preferred benefitting from enolate chemistry. So far, the regioselective *N*- α,β -desaturation of amides remains unknown (Scheme 1a).

Considering that the desaturation of amides is one of the most efficient and ideal approaches to enamides, many efforts have been made to realize the desaturation of amides. Early in the 1980s, Shono first accomplished this goal *via* a two-step reaction. Amides were initially oxidized to *N*- α -methoxyl amides¹³ and subsequently went through a methanol elimination process to yield the enamide product.¹⁴ Recently, trail-blazing work regarding the direct desaturation of amides has

been significantly achieved by the Gevorgyan group, which includes the generation of a hybrid aryl Pd-radical species under visible light irradiation and a HAT (hydrogen atom transfer) process to realize the desaturation reactions (Scheme 1b).¹⁵ Meanwhile, the desaturation of *N*-Boc, Cbz and Bz protected amides through manganese-catalyzed α -C(sp³)-H hydroxylation and electrophilic activation of amides was demonstrated by the groups of Groves and Maulide, respectively (Scheme 1c).¹⁶ Magnus's group reported the first example of α -azidation of amides and their analogues using TMSN₃ and 2-iodosobenzoic acid, with enamides as by-products (Scheme 1d).¹⁷ Despite the significance, a limitation is that substrates containing an acidic C(sp³)-H bond adjacent to the carbonyl group are not amenable for selective desaturation. Thus, general and efficient methods to furnish enamides from amides are highly desired and unrepresented. Herein, we report a general method to realize regioselective oxidative *N*- α,β -desaturation of amides to generate enamides. This transformation shows very broad substrate tolerance, and aroyl-, alkanoyl-, cyclic-, and acyclic-amides are all compatible. Besides, β -halogenated enamides can also be generated under slightly adjusted conditions, which can be further modified by a coupling reaction (Scheme 1e).



Fig. 1 Representative drugs containing enamide fragments.

^aState Key Laboratory of Natural and Biomimetic Drugs, Chemical Biology Center, School of Pharmaceutical Sciences, Peking University, Xue Yuan Rd. 38, Beijing 100191, China. E-mail: jiaoning@pku.edu.cn; ssong@bjmu.edu.cn

^bShanghai Key Laboratory of Green Chemistry and Chemical Processes, East China Normal University, Shanghai 200062, China

† Electronic supplementary information (ESI) available. CCDC 2097260. For ESI and crystallographic data in CIF or other electronic format see <https://doi.org/10.1039/d2sc02210a>

‡ These authors contributed equally.



Scheme 1 The significance and challenges for the synthesis of enamides from amides.

Results and discussion

The azide radical, which was an electron-deficient *N*-centered radical, was proved to be an efficient hydrogen-abstrating species in C(sp³)-H bond functionalization¹⁸ and plays versatile roles in different transformations.^{17–19} Hence, we attempted to use the azide radical to abstract more electron-rich *N*- α -C-H bonds to realize selective oxidation reaction of amides.²⁰ At the

very beginning, we tried to utilize NIS and azide to synthesize the highly reactive reagent IN₃ *in situ*,^{19e} initiating amide oxidative desaturation *via* a radical process. As initial attempts to realize the desaturation of amides, *N*-(4-methylbenzoyl) piperidine **1a** was selected as the model substrate, using NIS as the oxidant and NaN₃ as the azide source. To our delight, after screening solvents, we found that enamide **2a** was generated in ethyl acetate (EA) with moderate yield (Table 1, entry 2). NaN₃ was essential for this transformation (Table 1, entry 1). The iodine ion is one of the by-products in this reaction, but this conversion was inhibited when an excessive amount of NaI was used (Table 1, entry 3). To avoid the inhibiting effect of the excessive amount of by-product NaI, the oxidant NIS was replaced by PhI(OAc)₂ (PIDA), and the yield was reduced to 23% (Table 1, entry 4). During the screening of the amount of NaI and various catalysts (for more condition screening, see the ESI[†]), the yield was further raised to 64% when 30 mol% NaI and 10 mol% FeCl₂ was added (Table 1, entry 5). It is very interesting that the desaturated iodination product **3a** was obtained in 40% yield when more soluble TMSN₃ was added instead of NaN₃ (Table 1, entry 6). 2.5 equiv. of TMSN₃ and NIS with CCl₄ as the solvent could increase the isolated yield of **3a** to 65% (entry 7). Besides, no doubly dehydrogenated products were produced with a large excess of the N₃ reagent and oxidant. The rotamerism was observed from many enamide and *N*- β -halogenated enamide products, which is confirmed by variable-temperature ¹H NMR experiments (see ESI, Fig. S1[†]).²¹

With the optimal conditions in hand (Table 1, entry 5), we commenced investigating the scope of this reaction. At first, the influence of the *N*-acyl substituent was tested. As shown, this method is compatible for broad functional groups (Table 2). Simple *N*-aroyl amides underwent selective desaturation to furnish corresponding enamides in good yields. Urea (**2j**), *N*-carboxylate compound (**2k**), and tosyl amine (**2l**) were also applicable and provided the product in acceptable to good yields. It is noteworthy that *N*-alkanoyl amides worked well in this reaction with good yield. Benzyl amide (**2m**), acetamide (**2n**) and *tert*-butylamide (**2o**) could afford the desired product in good yields. Cyclopropyl amide was also dehydrogenated

Table 1 Screening of reaction conditions^a

Entry	Cat.	[N ₃]	Oxidant	Solvent	2a [%]	3a [%]
1	—	—	NIS (3.0 equiv.)	EA	0	0
2	—	NaN ₃ (3.0 equiv.)	NIS (3.0 equiv.)	EA	54	Trace
3 ^b	—	NaN ₃ (3.0 equiv.)	NIS (3.0 equiv.)	EA	15	0
4	—	NaN ₃ (3.0 equiv.)	PIDA (1.8 equiv.)	EA	23	0
5 ^c	FeCl ₂	NaN ₃ (3.6 equiv.)	PIDA (1.8 equiv.)	EA	71 (64)	0
6 ^d	—	TMSN ₃ (2.0 equiv.)	NIS (2.0 equiv.)	DCE	0	40
7 ^d	—	TMSN ₃ (2.5 equiv.)	NIS (2.5 equiv.)	CCl ₄	0	68 (65)

^a Reaction conditions: **1a** (0.4 mmol) and additives in EA (4.0 mL) under Ar, 80 °C, and 12 h. Determined by ¹H NMR analysis using 1,1,2,2-tetrachloroethane as the internal standard. Isolated yield in parentheses. ^b NaI (2.0 equiv.) as the additive. ^c NaI (30 mol%) as the additive. ^d **1a** (0.2 mmol) and open air reaction.



Table 2 Desaturation of *N*-acyl amides^a

^a Reaction conditions (Method A): reactions were conducted on a 0.4 mmol scale using 10 mol% FeCl₂, 30 mol% NaI, 1.8 equiv. PIDA, 3.6 equiv. NaN₃, in 4.0 mL EA, 80 °C, under an Ar atmosphere, and 12 h. Isolated yields.

successfully in good yield (2p). Chlorinated amide underwent this transformation in good yield with the chlorine functional group untouched (2r) without the detection of the S_N2 product. Especially, the ketone group (2s) and alkyne group (2t) can also be reserved under these oxidative conditions with good yields. Notably, high selective desaturation was observed in the presence of other carbonyl functional groups, for instance, ketone (2s) and ester (2u). Moreover, the desaturation of amides bearing seven- and eight-membered rings produced the corresponding enamides (2v and 2w) in moderate yields, and this method was able to apply in the synthesis of a thirteen-membered cyclic enamide (2x). The substituents on the piperidine showed little influence on the desaturation reaction, and substituted enamides (2y–2aa) were obtained in good yields.

We next tested the desaturation reaction of acyclic amides (Table 3). To our delight, when there were two identical substituents on amides, both *N*-alkanoyl and *N*-benzoyl acyclic amides were converted to the desired products in acceptable yields with high selectivity (2ab–2ae). Even in the presence of ester and ketone groups, no conjugated alkenyl product was observed in this oxidative desaturation reaction (2af and 2ag). For unsymmetrical *tert*-amides, lower regioselectivity was obtained when the steric effect was similar to alkyl groups (2ai and 2aj).

The β-halogenated enamides can be further modified to synthesize more sophisticated compounds *via* a well-developed

Table 3 Desaturation of acyclic amides^a

^a Reaction conditions (Method A): reactions were conducted on a 0.4 mmol scale using 10 mol% FeCl₂, 30 mol% NaI, 1.8 equiv. PIDA, 3.6 equiv. NaN₃, in 4.0 mL EA, 80 °C, under Ar atmosphere, and 12 h. Isolated yields.

transition metal-catalyzed cross-coupling reaction. The direct synthesis of β-halogenated enamides from amides has not been reported yet. We then tested the dehydrogenative halogenation of amides with NIS as the oxidant, TMSN₃ as the additive and CCl₄ as the solvent (Table 4). The scope of this transformation was set out for further investigation (Table 4). The structure of the β-iodine enamide was confirmed by X-ray single crystal diffraction (3c, CCDC 2097260). Additionally, the dehydrogenative *N*-β-bromination of amides was achieved with 1,3-dibromo-5,5-dimethylhydantoin (DBDMH) as the brominating reagent and TogniN₃ (ref. 18a) as the oxidant. The yields of the desired products were acceptable (Table 4). Among them, not only aroyl amide could furnish this transformation, but also alkanoyl amide could produce the desired product (3h). The *N*-β-halogenated enamide can be used to synthesize more complicated enamides by utilizing the classic coupling reaction.

In order to get a better insight into the mechanism, some control experiments were designed and carried out (Scheme 2). At first, the reaction was inhibited after adding 2,2,6,6-tetramethyl-piperidine-*N*-oxyl (TEMPO) or 2,6-di-*tert*-butyl-4-methylphenol (BHT) into the reaction system (Method A), and the starting materials remained (Scheme 2a), indicating that the radical process might be part of the dehydrogenation transformation. The radical clock experiment was also carried out, but no ring opening dehydrogenation product was detected under the standard conditions (Scheme 2b). This result may not deny the free radical process because the radical with the intact cyclopropane is likely more stable than the corresponding homoallylic primary radical. Moreover, five-membered ring amide (1al) and secondary amide (1am) did not produce the dehydrogenation product but *N*-α-azide substituted amides were produced (4al and 4am), which are very stable compounds.¹⁷ It reveals that the carbocation intermediates may



Table 4 Dehydrogenative *N*- β -halogenation of amides^a

^a Reaction conditions (Method B): reactions were conducted on a 0.2 mmol scale using 2.5 equiv. NIS, 2.5 equiv. TMSN₃ in 2.0 mL CCl₄, 80 °C, under an Ar atmosphere, and 7 h. Isolated yields.

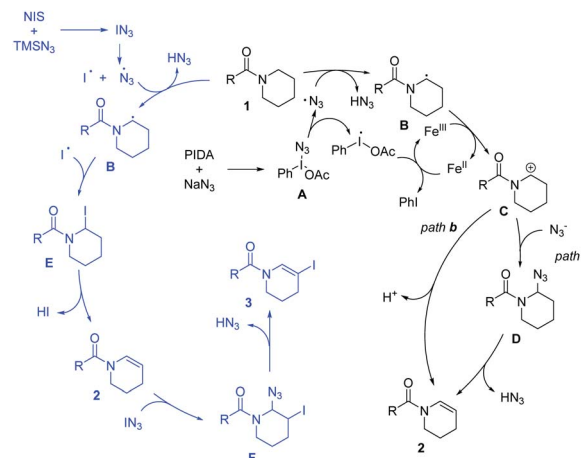
^b Reaction conditions (Method C): reactions were conducted on a 0.3 mmol scale using 0.55 equiv. 1,3-dibromo-5,5-dimethylhydantoin (DBDMH), 1.1 equiv. TogniN₃ in 2.0 mL DCE, 80 °C, under an Ar atmosphere, and 12 h. Isolated yields.



Scheme 2 Mechanistic studies.

be key intermediates in this process (Scheme 2c). In addition, intermediate **5** was isolated under the standard conditions (Method B, Scheme 2d). Furthermore, we monitored the reaction process by *in situ* ¹H-NMR (see ESI, Fig. S2†). With the extension of reaction time, the intermediate **5** gradually increased and reached the peak in 4 hours, and then it was gradually converted to **3a**. This demonstrated that the *N*- α -azide- β -halogenated amide is the key intermediate in the dehydrogenative halogenation reaction.

On the basis of the above experiments, a plausible mechanism was proposed (Scheme 3). The azide radical is generated *in situ* through two pathways under different conditions. Initial ligand exchange between PIDA and NaN₃ would afford intermediate **A**, which undergoes thermal homolytic cleavage owing



Scheme 3 Mechanistic investigations.

to a weak I–N bond to generate an azide radical.^{19g,n} Another pathway to generate the azide radical is the decomposition of IN₃, which is produced from NIS and TMSN₃.^{19e} Then the radical intermediate **B** is produced *via* hydrogen abstraction by the azide radical.^{18a,19v} Subsequently, intermediate **B** is converted to cationic intermediate **C** through a single electron oxidation process promoted by FeCl₂.²² The enamide can be also generated *via* two pathways from intermediate **B**. In path a, the nucleophilic addition of intermediate **C** by the azide anion occurs to generate intermediate **D**, which produces product **2** *via* the elimination of HN₃ (path a). Alternatively, enamide **2** can be generated directly from intermediate **C** *via* deprotonation (path b). Regarding the dehydrogenative *N*- β -halogenation of amide process, intermediate **B** combines with the iodine radical to obtain intermediate **E**,^{19o} which will further transform into **2** by elimination. Then, enamide **2** undergoes addition quickly with IN₃ affording the key intermediate **F**. Finally, the desired product *N*- β -halogenated enamide **3** is formed with the concomitant elimination of the HN₃ unit. The different electrophilicity of NIS and the different active azide intermediates in different solvents might account for the selective formation of the terminal product.

Conclusions

In summary, we described a novel, general and regioselective oxidative *N*- α , β -desaturation and dehydrogenative *N*- β -halogenation of amides. This chemistry features excellent functional group compatibility, and thus provides efficient and general access to enamides and β -halogenated enamides, which are biologically important scaffolds and versatile organic building blocks in pharmaceutical sciences and synthetic organic chemistry.

Author contributions

X. L., Z. C., S. S. and N. J. conceived and designed the experiments. X. L. and Z. C. carried out most of the experiments. X. L., Z. C., J. L., Z. Z., S. S. and N. J. analyzed the data. X. L., Z. C., S. S. and N. J. wrote the paper. N. J. directed the research.



Conflicts of interest

There are no conflicts to declare.

Acknowledgements

We acknowledge the National Key R&D Program of China (No. 2021YFA1501700), the NSFC (No. 22131002, 22071005, and 22161142019), the Beijing Nova Program (No. Z201100006820099), and the Tencent Foundation for financial support. We thank Cheng Zhang in this group for reproducing the reactions of **2q** and **3e**.

Notes and references

- M. Perez-Sayans, J. M. Somoza-Martin, F. Barros-Angueira, J. M. Rey and A. Garcia-Garcia, *Cancer Treat. Rev.*, 2009, **35**, 707–713.
- (a) D. R. Carbery, *Org. Biomol. Chem.*, 2008, **6**, 3455–3460; (b) K. Gopalaiyah and H. B. Kagan, *Chem. Rev.*, 2011, **111**, 4599–4657; (c) G. Masson and G. Bernadat, *Synlett*, 2014, **25**, 2842–2867; (d) G. Masson, T. Courant and G. Dagousset, *Synthesis*, 2015, **47**, 1799–1856; (e) M. X. Wang, *Chem. Commun.*, 2015, **51**, 6039–6049.
- (a) F. Pohlki and S. Doye, *Chem. Soc. Rev.*, 2003, **32**, 104–114; (b) J. R. Dehli, J. Legros and C. Bolm, *Chem. Commun.*, 2005, 973–986.
- (a) R. P. Linstead, E. A. Braude, P. W. D. Mitchell, K. R. H. Wooldridge and L. M. Jackman, *Nature*, 1952, **169**, 100–103; (b) E. A. Mamedov and V. Cortés Corberán, *Appl. Catal., A*, 1995, **127**, 1–40; (c) H. H. Kung and M. C. Kung, *Appl. Catal., A*, 1997, **157**, 105–116; (d) L. M. Madeira and M. F. Portela, *Catal. Rev.*, 2002, **44**, 247–286; (e) X. Zhang, A. Fried, S. Knapp and A. S. Goldman, *Chem. Commun.*, 2003, 2060–2061; (f) S. Wang and Z. H. Zhu, *Energy Fuels*, 2004, **18**, 1126–1139; (g) M. B. Ansari and S.-E. Park, *Energy Environ. Sci.*, 2012, **5**, 9419; (h) M. T. Schümperli, C. Hammond and I. Hermans, *ACS Catal.*, 2012, **2**, 1108–1117; (i) A.-F. Voica, A. Mendoza, W. R. Gutekunst, J. O. Fraga and P. S. Baran, *Nat. Chem.*, 2012, **4**, 629–635; (j) S. Wertz and A. Studer, *Green Chem.*, 2013, **15**, 3116; (k) B. Chen, L. Wang and S. Gao, *ACS Catal.*, 2015, **5**, 5851–5876; (l) R. A. Sheldon, *Catal. Today*, 2015, **247**, 4–13; (m) A. E. Wendlandt and S. S. Stahl, *Angew. Chem., Int. Ed.*, 2015, **54**, 14638–14658; (n) M. J. Zhou, S. F. Zhu and Q. L. Zhou, *Chem. Commun.*, 2017, **53**, 8770–8773.
- (a) I. Göttker-Schnetmann, P. White and M. Brookhart, *J. Am. Chem. Soc.*, 2004, **126**, 1804–1811; (b) A. D. Bolig and M. Brookhart, *J. Am. Chem. Soc.*, 2007, **129**, 14544–14545; (c) R. Giri, N. Maugel, B. M. Foxman and J.-Q. Yu, *Organometallics*, 2008, **27**, 1667–1670; (d) G. E. Dobereiner and R. H. Crabtree, *Chem. Rev.*, 2010, **110**, 681–703; (e) T. C. Johnson, D. J. Morris and M. Wills, *Chem. Soc. Rev.*, 2010, **39**, 81–88; (f) J. Choi, A. H. MacArthur, M. Brookhart and A. S. Goldman, *Chem. Rev.*, 2011, **111**, 1761–1779; (g) C. Gunanathan and D. Milstein, *Science*, 2013, **341**, 1229712; (h) C. B. Bheeter, R. Jin, J. K. Bera, P. H. Dixneuf and H. Doucet, *Adv. Synth. Catal.*, 2014, **356**, 119–124; (i) W. Yao, Y. Zhang, X. Jia and Z. Huang, *Angew. Chem., Int. Ed.*, 2014, **53**, 1390–1394; (j) S. Werkmeister, J. Neumann, K. Junge and M. Beller, *Chemistry*, 2015, **21**, 12226–12250; (k) A. Kumar, T. M. Bhatti and A. S. Goldman, *Chem. Rev.*, 2017, **117**, 12357–12384; (l) L. Huang, A. Bismuto, S. A. Rath, N. Trapp and B. Morandi, *Angew. Chem., Int. Ed.*, 2021, **60**, 7290–7296.
- (a) K. Nomura and Y. Saito, *J. Chem. Soc., Chem. Commun.*, 1988, 161–162; (b) S. Toshiyasu, S. Touru, T. Yuko and T. Masato, *Chem. Lett.*, 1988, **17**, 263–264; (c) J. A. Maguire, W. T. Boese and A. S. Goldman, *J. Am. Chem. Soc.*, 1989, **111**, 7088–7093; (d) A. J. Esswein and D. G. Nocera, *Chem. Rev.*, 2007, **107**, 4022–4047; (e) X. Sun, J. Chen and T. Ritter, *Nat. Chem.*, 2018, **10**, 1229–1233; (f) W. M. Cheng, R. Shang and Y. Fu, *Nat. Commun.*, 2018, **9**, 5215; (g) J. G. West, D. Huang and E. J. Sorensen, *Nat. Commun.*, 2015, **6**, 10093.
- (a) T. Shono, Y. Matsumura and Y. Nakagawa, *J. Am. Chem. Soc.*, 1974, **96**, 3532–3536; (b) T. Shono, M. Okawa and I. Nishiguchi, *J. Am. Chem. Soc.*, 1975, **97**, 6144–6147; (c) M. Okimoto, Y. Takahashi, K. Numata and G. Sasaki, *Heterocycles*, 2005, **65**, 371–375; (d) Y. Wu, H. Yi and A. Lei, *ACS Catal.*, 2018, **8**, 1192–1196; (e) R. J. Perkins, R. Feng, Q. Lu and K. D. Moeller, *Chin. J. Chem.*, 2019, **37**, 672–678; (f) M. Bugnola, K. Shen, E. Haviv and R. Neumann, *ACS Catal.*, 2020, **10**, 4227–4237; (g) S. Gnaim, Y. Takahira, H. R. Wilke, Z. Yao, J. Li, D. Delbrayelle, P. G. Echeverria, J. C. Vantourout and P. S. Baran, *Nat. Chem.*, 2021, **13**, 367–372.
- (a) H. J. Reich and S. Wollowitz, *Org. React.*, 2004, 1–296; (b) J. Muzart, *Eur. J. Org. Chem.*, 2010, **2010**, 3779–3790; (c) S. S. Stahl and T. Diao, in *Comprehensive Organic Synthesis II*, ed. P. Knochel, Elsevier, Amsterdam, 2nd edn, 2014, pp. 178–212; (d) T. Newhouse, A. Turlik and Y. Chen, *Synlett*, 2015, **27**, 331–336.
- (a) R. J. Theissen, *J. Org. Chem.*, 1971, **36**, 752–757; (b) R. C. Larock, T. R. Hightower, G. A. Kraus, P. Hahn and D. Zheng, *Tetrahedron Lett.*, 1995, **36**, 2423–2426; (c) T. Diao and S. S. Stahl, *J. Am. Chem. Soc.*, 2011, **133**, 14566–14569; (d) T. Diao, T. J. Wadzinski and S. S. Stahl, *Chem. Sci.*, 2012, **3**, 887–891; (e) T. Diao, D. Pun and S. S. Stahl, *J. Am. Chem. Soc.*, 2013, **135**, 8205–8212; (f) X. Jie, Y. Shang, X. Zhang and W. Su, *J. Am. Chem. Soc.*, 2016, **138**, 5623–5633; (g) Y. Sakamoto, T. Amaya, T. Suzuki and T. Hirao, *Chem.–Eur. J.*, 2016, **22**, 18686–18689; (h) Y. Shang, X. Jie, K. Jonnada, S. N. Zafar and W. Su, *Nat. Commun.*, 2017, **8**, 2273; (i) D. Huang, Y. Zhao and T. R. Newhouse, *Org. Lett.*, 2018, **20**, 684–687; (j) H. Li, Q. Jiang, X. Jie, Y. Shang, Y. Zhang, L. J. Goossen and W. Su, *ACS Catal.*, 2018, **8**, 4777–4782.
- Y.-R. Luo, *Comprehensive Handbook of Chemical Bond Energies*, CRC Press, Boca Raton, 2007.
- (a) Y. Chen, J. P. Romaine and T. R. Newhouse, *J. Am. Chem. Soc.*, 2015, **137**, 5875–5878; (b) S. M. Szweczyk, Y. Zhao, H. A. Sakai, P. Dube and T. R. Newhouse, *Tetrahedron*, 2018, **74**, 3293–3300.



- 12 (a) Y. Chen, A. Turlik and T. R. Newhouse, *J. Am. Chem. Soc.*, 2016, **138**, 1166–1169; (b) M. Chen and G. Dong, *J. Am. Chem. Soc.*, 2017, **139**, 7757–7760; (c) M. Chen, A. J. Rago and G. Dong, *Angew. Chem., Int. Ed.*, 2018, **57**, 16205–16209; (d) Z. Wang, Z. He, L. Zhang and Y. Huang, *J. Am. Chem. Soc.*, 2018, **140**, 735–740; (e) M. Chen and G. Dong, *J. Am. Chem. Soc.*, 2019, **141**, 14889–14897; (f) C. J. Teskey, P. Adler, C. R. Goncalves and N. Maulide, *Angew. Chem., Int. Ed.*, 2019, **58**, 447–451.
- 13 T. Shono, H. Hamaguchi and Y. Matsumura, *J. Am. Chem. Soc.*, 1975, **97**, 4264–4268.
- 14 T. Shono, Y. Matsumura, K. Tsubata, Y. Sugihara, S. Yamane, T. Kanazawa and T. Aoki, *J. Am. Chem. Soc.*, 1982, **104**, 6697–6703.
- 15 (a) P. Chuentragool, M. Parasram, Y. Shi and V. Gevorgyan, *J. Am. Chem. Soc.*, 2018, **140**, 2465–2468; (b) M. Parasram, P. Chuentragool, D. Sarkar and V. Gevorgyan, *J. Am. Chem. Soc.*, 2016, **138**, 6340–6343; (c) P. Chuentragool, D. Kurandina and V. Gevorgyan, *Angew. Chem., Int. Ed.*, 2019, **58**, 11586–11598; (d) M. Ratushnyy, N. Kvasovs, S. Sarkar and V. Gevorgyan, *Angew. Chem., Int. Ed.*, 2020, **59**, 10316–10320.
- 16 (a) G. Li, P. A. Kates, A. K. Dilger, P. T. Cheng, W. R. Ewing and J. T. Groves, *ACS Catal.*, 2019, **9**, 9513–9517; (b) P. Spiess, M. Berger, D. Kaiser and N. Maulide, *J. Am. Chem. Soc.*, 2021, **143**, 10524–10529.
- 17 P. Magnus, C. Hulme and W. Weber, *J. Am. Chem. Soc.*, 1994, **116**, 4501–4502.
- 18 (a) Y. Wang, X. Hu, C. A. Morales-Rivera, G. X. Li, X. Huang, G. He, P. Liu and G. Chen, *J. Am. Chem. Soc.*, 2018, **140**, 9678–9684; (b) T. Liu, M. C. Myers and J. Q. Yu, *Angew. Chem., Int. Ed.*, 2017, **56**, 306–309; (c) P. T. Rabet, G. Fumagalli, S. Boyd and M. F. Greaney, *Org. Lett.*, 2016, **18**, 1646–1649; (d) T. Liu, T. S. Mei and J. Q. Yu, *J. Am. Chem. Soc.*, 2015, **137**, 5871–5874.
- 19 (a) K. Gollnick, D. Haisch and G. Schade, *J. Am. Chem. Soc.*, 1972, **94**, 1747–1748; (b) D. A. Armstrong, M. Farahani and P. S. Surdhar, *Can. J. Chem.*, 1990, **68**, 1974–1978; (c) M. S. Workentin, B. D. Wagner, J. Luszytk and D. D. M. Wayner, *J. Am. Chem. Soc.*, 1995, **117**, 119–126; (d) V. V. Zhdankin, A. P. Krasutsky, C. J. Kuehl, A. J. Simonsen, J. K. Woodward, B. Mismash and J. T. Bolz, *J. Am. Chem. Soc.*, 1996, **118**, 5192–5197; (e) A. Hassner, L. Marinescu and M. Bols, *Encyclopedia of Reagents for Organic Synthesis*, 2005; (f) A. G. Griesbeck, M. Reckenthaler and J. Uhlig, *Photochem. Photobiol. Sci.*, 2010, **9**, 775–778; (g) K. Matcha and A. P. Antonchick, *Angew. Chem., Int. Ed.*, 2013, **52**, 2082–2086; (h) G. Fumagalli, P. T. Rabet, S. Boyd and M. F. Greaney, *Angew. Chem., Int. Ed.*, 2015, **54**, 11481–11484; (i) M. Z. Lu, C. Q. Wang and T. P. Loh, *Org. Lett.*, 2015, **17**, 6110–6113; (j) A. Sharma and J. F. Hartwig, *Nature*, 2015, **517**, 600–604; (k) B. Olofsson, in *Hypervalent Iodine Chemistry*, ed. T. Wirth, Springer International Publishing, Cham, 2016, pp. 135–166; (l) Y. Wang, G. X. Li, G. Yang, G. He and G. Chen, *Chem. Sci.*, 2016, **7**, 2679–2683; (m) Y. A. Yuan, D. F. Lu, Y. R. Chen and H. Xu, *Angew. Chem., Int. Ed.*, 2016, **55**, 534–538; (n) P. Magnus and J. Lacour, *J. Am. Chem. Soc.*, 1992, **114**, 767–769; (o) J. Barluenga, E. Campos-Gomez, D. Rodriguez, F. Gonzalez-Bobes and J. M. Gonzalez, *Angew. Chem., Int. Ed.*, 2005, **44**, 5851–5854; (p) N. Fu, G. S. Sauer, A. Saha, A. Loo and S. Lin, *Science*, 2017, **357**, 575–579; (q) C. E. Hendrick, K. J. Bitting, S. Cho and Q. Wang, *J. Am. Chem. Soc.*, 2017, **139**, 11622–11628; (r) Y. Wang, N. Wang, J. Zhao, M. Sun, H. You, F. Fang and Z.-Q. Liu, *ACS Catal.*, 2020, **10**, 6603–6612; (s) T. G. Driver, *Org. Biomol. Chem.*, 2010, **8**, 3831–3846; (t) K. Shin, H. Kim and S. Chang, *Acc. Chem. Res.*, 2015, **48**, 1040–1052; (u) P. Sivaguru, Y. Ning and X. Bi, *Chem. Rev.*, 2021, **121**, 4253–4307; (v) W. Zhou, L. Zhang and N. Jiao, *Angew. Chem., Int. Ed.*, 2009, **48**, 7094–7097; (w) T. Wang and N. Jiao, *J. Am. Chem. Soc.*, 2013, **135**, 11692–11695; (x) T. Wang and N. Jiao, *Acc. Chem. Res.*, 2014, **47**, 1137–1145; (y) X. Sun, X. Li, S. Song, Y. Zhu, Y. F. Liang and N. Jiao, *J. Am. Chem. Soc.*, 2015, **137**, 6059–6066; (z) J. Liu, X. Qiu, X. Huang, X. Luo, C. Zhang, J. Wei, J. Pan, Y. Liang, Y. Zhu, Q. Qin, S. Song and N. Jiao, *Nat. Chem.*, 2019, **11**, 71–77.
- 20 F. Parsaee, M. C. Senarathna, P. B. Kannangara, S. N. Alexander, P. D. E. Arche and E. R. Welin, *Nat. Rev. Chem.*, 2021, **5**, 486–499.
- 21 R. E. Quinones, C. M. Glinkerman, K. Zhu and D. L. Boger, *Org. Lett.*, 2017, **19**, 3568–3571.
- 22 K. Nakajima, Y. Miyake and Y. Nishibayashi, *Acc. Chem. Res.*, 2016, **49**, 1946–1956.

