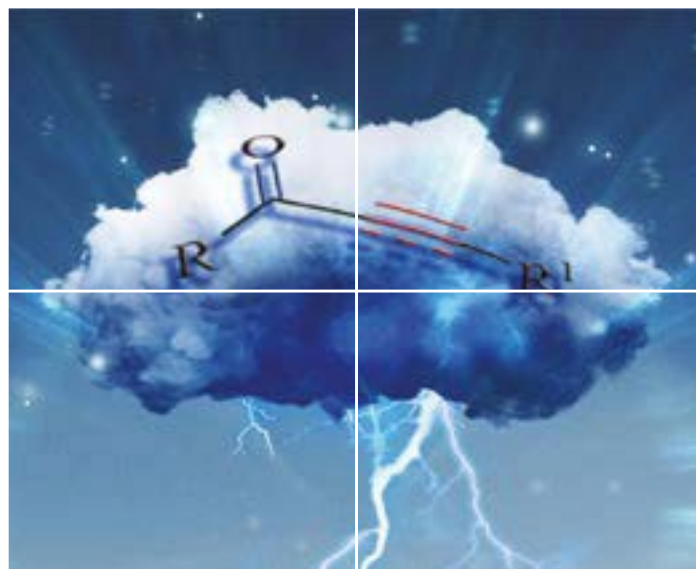


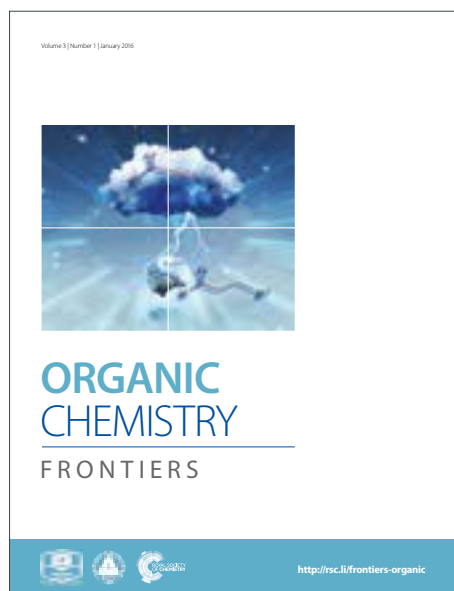
ORGANIC CHEMISTRY

FRONTIERS

Accepted Manuscript



This article can be cited before page numbers have been issued, to do this please use: W. Shang, S. Li, Y. Ding, Z. Pan, X. Tong and C. Xia, *Org. Chem. Front.*, 2017, DOI: 10.1039/C7QO00389G.



This is an Accepted Manuscript, which has been through the Royal Society of Chemistry peer review process and has been accepted for publication.

Accepted Manuscripts are published online shortly after acceptance, before technical editing, formatting and proof reading. Using this free service, authors can make their results available to the community, in citable form, before we publish the edited article. We will replace this Accepted Manuscript with the edited and formatted Advance Article as soon as it is available.

You can find more information about Accepted Manuscripts in the [author guidelines](#).

Please note that technical editing may introduce minor changes to the text and/or graphics, which may alter content. The journal's standard [Terms & Conditions](#) and the ethical guidelines, outlined in our [author and reviewer resource centre](#), still apply. In no event shall the Royal Society of Chemistry be held responsible for any errors or omissions in this Accepted Manuscript or any consequences arising from the use of any information it contains.



Journal Name

ARTICLE

Transition-Metal-Free Dehydrogenation Coupling of Pyridinium through Self-Promoted Hydride Transfer Process

Wenbin Shang,^{a,c} Shanyong Li,^{a,c} Yuzhen Ding,^b Zhiqiang Pan,^b Xiaogang Tong^b and Chengfeng Xia^{*a,b}

Received 00th January 20xx,
Accepted 00th January 20xx

DOI: 10.1039/x0xx00000x

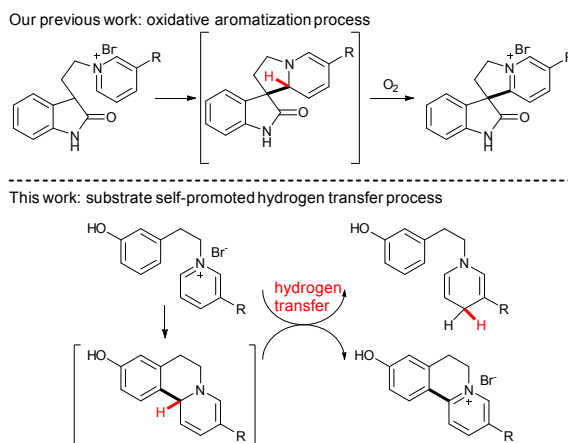
www.rsc.org/

A transition-metal-free intramolecular cross dehydrogenation coupling reaction of pyridinium was developed. The C(sp²)-H/C(sp²)-H coupling reaction involved an unprecedented intermolecular hydride transfer process from the 1,2-dihydropyridine intermediate to another molecule of pyridinium and formed the 1,4-dihydropyridine. Unlike the well-known dehydrogenation coupling proceeded in oxidative conditions, this was the first example of coupling reaction through substrate self-promoted hydride transfer process.

Introduction

The direct C-H functionalization of pyridine is a key goal in modern organic chemistry,¹ which remains a significant challenge due to the poor chemoselectivity and the lower energy of the π -system relative to benzene.² These factors have led to the use of pyridine derivatives functionalized at nitrogen to generate cationic pyridinium species, which can be more electrophilic than the unactivated parent heterocycle.³ Therefore, a pre-activation of the pyridine ring such as *N*-oxidation,⁴ *N*-acylation,⁵ *N*-alkylation⁶, or Lewis acid-mediation^{1b,7} is usually required. Furthermore, the popularity of pyridinium species lies in their high reactivity, ease of synthesis, and inexpensive commercial available chemicals.⁶

Over the past decades, transition-metal mediated C-H activation has proven to be valuable in functionalization of pyridinium and seminal advances have been achieved.^{3b, 8} Moreover, several transition-metal-free coupling reactions of pyridinium have been succeeded.^{7,9} Previously, we reported a transition-metal-free intramolecular dehydrogenation coupling C(sp³)-H/C(sp²)-H of pyridinium through an oxidative aromatization process to construct the spirooxindole skeleton.¹⁰ Herein, we reported a unique transition-metal-free intramolecular cross-coupling reaction between pyridinium and phenol moieties. Unlike the well-known oxidative aromatization process,^{9c, 9d, 9f, 10} this is the first example of substrate self-promoted hydride transfer process to realize the



Scheme 1 Dehydrogenation coupling of pyridinium.

dehydrogenation coupling reaction (Scheme 1).

Results and discussion

The substrate pyridinium **1** was readily prepared by quaternization of 5-(2-bromoethyl)-2-methoxyphenol with 3-acetylpyridine under solvent-free condition. At the beginning of our study, we first treated the pyridinium **1** with Na₂CO₃ in MeCN at 50 °C under air atmosphere. The desired coupling product **2** was obtained in 15% yield (Table 1, entry 1). During the reaction, we observed that both of the substrate and product were poor soluble in MeCN and proposed that increasing the solubility should facilitate the reaction. Shifting the solvent from MeCN to DMSO resulted in an improved yield in 42% (Table 1, entry 2). In other polar solvents, such as DMF or water, the coupling product **2** was also generated in moderated yields. Encouraged by these results, we screened more solvents and discovered that when the coupling reaction

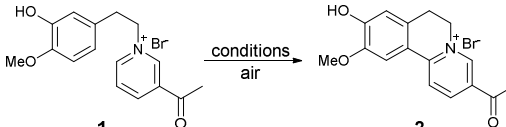
^a State Key Laboratory of Phytochemistry and Plant Resources in West China, Kunming Institute of Botany, Chinese Academy of Sciences, 132 Lanhei Road, Kunming 650201, China. E-mail: xiaof@ynu.edu.cn

^b Key Laboratory of Medicinal Chemistry for Natural Resources, Ministry of Education, School of Chemical Science and Technology, Yunnan University, 2 North Cuihu Road, Kunming 650091, China.

^c University of Chinese Academy of Sciences, Beijing 100049, China.

Electronic Supplementary Information (ESI) available: General procedures, figures and NMR spectra. See DOI: 10.1039/x0xx00000x

ARTICLE

Table 1. Optimization of the Reaction Conditions.^a


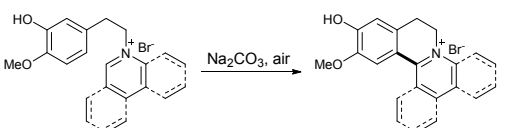
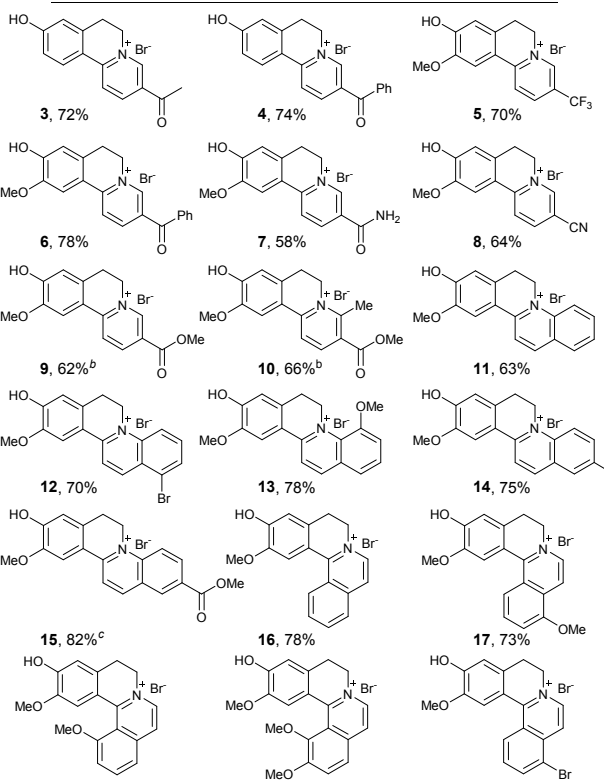
Entry	Solvent	Base	Yield(%) ^b
1	MeCN	Na ₂ CO ₃	15
2	DMSO	Na ₂ CO ₃	42
3	DMF	Na ₂ CO ₃	58
4	H ₂ O	Na ₂ CO ₃	57
5	EtOH	Na ₂ CO ₃	65
6	MeOH	Na ₂ CO ₃	76
7 ^c	TFE	Na ₂ CO ₃	82
8	MeOH	NaOH	68
9	MeOH	K ₂ CO ₃	70
10	MeOH	Cs ₂ CO ₃	56
11	MeOH	NaHCO ₃	14
12	MeOH	DBU	47
13	MeOH	TEA	18

^a Reactions were performed with **1** (0.1 mmol) and base (0.12 mmol) at 50 °C for 2 h under air atmosphere. ^b Isolated yields by silica gel column. ^c The reaction was performed with **1** (0.1 mmol) and base (0.3 mmol) in TFE (5 mL) at 50 °C under air atmosphere and the reaction time was extended to 18 h.

was conducted in MeOH, the reaction was considerably improved and afforded the coupling product **2** in 76% yield (Table 1, entry 6). It was found that the highest yield was obtained when TFE was used as the solvent. However, we noticed that the solvent MeOH was superior to TFE when other pyridinium substrates were subjected. Moreover, more equivalents of base and longer reaction time were required for the TFE conditions (Table 1, entry 7). Thus the further optimizations and substrate scope investigations were performed in MeOH. Changing the base from Na₂CO₃ to NaOH, K₂CO₃, or Cs₂CO₃ resulted in lower yields. When NaHCO₃ was employed as base, only 14% yield was obtained. The organic bases, DBU and TEA, were also screened for the coupling reaction (Table 1, entries 12 and 13). But the reaction did not proceed efficiently compared with Na₂CO₃.

With the optimized reaction conditions, different substrates were tested to extend the scope of this methodology (Table 2). It was found that the phenol moiety was an essential functional group for the coupling reaction. If the phenol was masked by methylation, the reaction did not proceed. Good yields were obtained regardless of ketone, trifluoromethyl, amide, or cyano groups on the pyridinium (compounds **5**, **6**, **7**, and **8**). For the substrates with ester group, the ester was easily saponified when the reaction was conducted in MeOH. In order to avoid saponification of substrates, the coupling reactions were performed in MeCN in a diluted manner to overcome the low solubility, and the products were obtained in satisfactory yields (compounds **9** and **10**). When there was an additional substitution group (such as bromo-) on the C-5 position of pyridinium, no coupling product was identified. This might be due to the steric hindrance and preventing the two reaction sites interaction. Moreover, no reaction was observed

when there was no electron-withdrawing group at the pyridinium moiety.

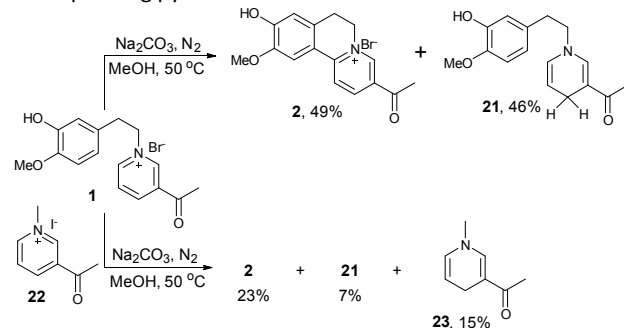
Table 2. Scope of dehydrogenation coupling.^a



3 , 72%	4 , 74%	5 , 70%
6 , 78%	7 , 58%	8 , 64%
9 , 62% ^b	10 , 66% ^b	11 , 63%
12 , 70%	13 , 78%	14 , 75%
15 , 82% ^c	16 , 78%	17 , 73%
18 , 71%	19 , 67%	20 , 75%

^a Unless otherwise noted, all reactions were performed with substrate (0.1 mmol), Na₂CO₃ (0.12 mmol) in MeOH (5 mL) at 50 °C for 2 h under air atmosphere. ^b MeCN was used as solvent and the reaction time was prolonged to 12 h. ^c Compound **15** was achieved in one pot through quaternization between **1** (0.1 mmol) and methyl quinoline-6-carboxylate (0.3 mmol) at 70 °C under solvent-free condition for 5 h.

Besides the pyridinium, the quinolinium and isoquinolinium substrates were also examined in the coupling conditions (Table 2). Unlike the requirement of electron-withdrawing group on pyridinium, a wide range of different functional groups were tolerable for the coupling reactions, such as unsubstituted quinolinium and isoquinolinium (compounds **11** and **16**), or halo derivatives (such as compounds **12**, **14**, and **20**). When the substrates were substituted with electron-donating groups, such as one or two methoxyl groups (such as compounds **13**, **17**, **18** and **19**), the coupling reactions proceeded smoothly and the products were afforded in good yields too. Interestingly, the coupling reaction directly occurred during the step of quaternization without further alkali treatment when a strong electron-withdrawing substituted quinoline derivative was explored (compound **15**).

Originally, we considered that this coupling reaction ($C(sp^2)-H/C(sp^2)-H$) involved the similar mechanism as our previous work for spirooxindole ($C(sp^3)-H/C(sp^2)-H$) through an oxygen promoted oxidative aromatization process.¹⁰ However, when a controlled reaction was performed in the glove box without oxygen, the coupling product **2** was still generated in 49% yield. These results indicated that oxygen was not required in the dehydrogenation coupling reactions. It was reported that hydrogen gas was released in some dehydrogenation reactions when no oxidants were involved.¹¹ Nevertheless, we did not detect any hydrogen release according to the standard hydrogen-measurement procedures.^{11a} Besides the isolation of coupling product **2**, another compound 1,4-dihydropyridine **21** was also afforded in 46% yield (Scheme 2). The generation of the 1,4-dihydropyridine **21** indicated that another molecule of pyridinium **1** served as a hydride acceptor in the manner of substrate self-promoted process. Most of reported dehydrogenation coupling reactions were carried out under oxidative conditions or with another different molecule as hydride acceptor.¹² This was the first example of dehydrogenation coupling reaction which was promoted by substrate itself. Moreover, the dehydrogenation coupling reaction involved hydride transfer process went through a reversed reaction pathway compared with Hantzsch ester, in which hydride transfers from 1,4-dihydropyridine to give the corresponding pyridinium.¹³



Scheme 2 Hydride transfer process occurred instead if oxidative process.

To confirm the existence of substrate self-promoted hydride transfer process, three controlled experiments were investigated. A competitive pyridinium **22** was added to the reaction mixtures as hydride acceptor. Besides the isolations of coupling product **2** (23% yield) and the 1,4-dihydropyridine **21** (7% yield), a new 1,4-dihydropyridine **23** (15% yield) was obtained (Scheme 2). The generation of 1,4-dihydropyridine **23** verified that the hydride transfer reaction occurred between the reaction intermediate and another one molecule of pyridinium. Furthermore, the amounts of coupling product **2** and hydrogenation product 1,4-dihydropyridine were afforded in around 1:1 ratio (Scheme 2). A two-hour dynamic NMR test of the coupling reaction of pyridinium **1** in MeOH at nitrogen atmosphere also revealed that equal amounts of **2** and **21** were produced simultaneously (Figure 1a and supporting information S16). An analogue of compound **1** with deuterium

labelling at C-6 of pyridinium **1** [D] was subjected to the reaction conditions and the deuterium was observed to be completely incorporated into C-4 of 1,4-dihydropyridine **21** [D] (Figure 1b and supporting information S17). All these evidences clearly demonstrated that the hydride transfer took place through pyridinium self-promoted process.

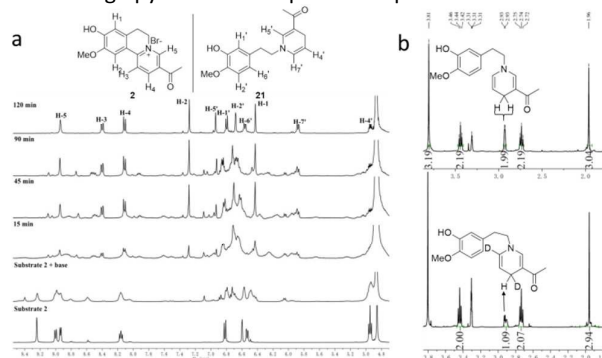
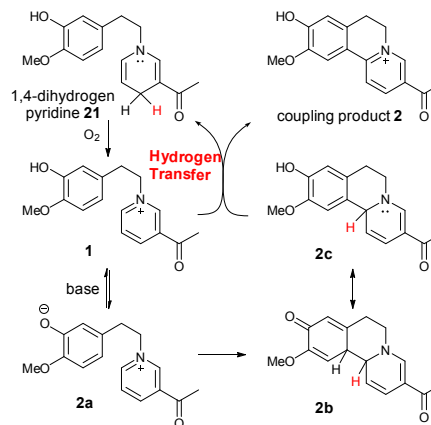


Figure 1 a. Dynamic NMR experiment b. Deuterium labeling experiment.

We considered that if one molecule of the starting substrate pyridinium **1** was served as hydride acceptor, then only half amount of the pyridinium **1** was converted to the coupling product **2** and the yield should be less than 50% instead of 76% in methanol. Moreover, no 1,4-dihydropyridine product **21** was observed when the reaction was conducted under air conditions. We surmised that 1,4-dihydropyridine **21** might be recycled to the starting substrate pyridinium **1** by oxygen. The purified 1,4-dihydropyridine **21** was dissolved in MeOH, and the reaction mixture was heated to 50 °C and stirred under oxygen. After 2h, the pyridinium **1** was generated and harvested in 75% yield after purification by silica gel column (supporting information S18). This experiment illustrated that the oxygen was not involved the dehydrogenation coupling process, but recycled the 1,4-dihydropyridine **21** to pyridinium **1**.¹⁴



Scheme 3 Proposed mechanism of the coupling reaction

On basis of the above experimental results, a possible mechanism was depicted as in scheme 4. The pyridinium **1** was nucleophilically attacked by the phenol moiety under base

ARTICLE

Journal Name

conditions to give intermediate **2b**. After the ensuing phenol-quinone tautomerism, an intermolecular hydride transfer process occurred between the intermediate **2c** and the pyridinium **1** to give the coupling product **2** along with the 1,4-dihydropyridine **21**. In the presence of oxygen, the 1,4-dihydropyridine **21** was recycled to pyridinium **1** via oxidative aromatization.

Conclusions

In conclusion, we have developed an intramolecular cross dehydrogenation coupling reaction that gave access to functionally pyridinium, quinolinium, and isoquinolinium without the existence of transitional metal catalysts. The C(sp²)-H/C(sp²)-H coupling has been achieved via the mild, operationally simple reaction, thus gave a new example for the direct arylation of π -deficient heteroarenes. Mechanistic studies showed that the coupling product proceeded through a unique substrate self-promoted hydride transfer process.

Acknowledgements

This work was financially supported by the National Natural Science Foundation of China (21572236, 21602193, and 21603194), the Natural Science Foundation of Yunnan Province (2014FA008 and 2015FB167), and the Program for Changjiang Scholars and Innovative Research Team in University (IRT13095).

Notes and references

- 1 For recent examples of C-H functionalization: (a) J. Jin and D. W. C. MacMillan, *Angew. Chem. Int. Ed.*, 2015, **54**, 1565-1569; (b) M. Murakami and S. Hori, *J. Am. Chem. Soc.*, 2003, **125**, 4720-4721; (c) K. Godula, B. Sezen and D. Sames, *J. Am. Chem. Soc.*, 2005, **127**, 3648-3649; (d) J. C. Lewis, R. G. Bergman and J. A. Ellman, *J. Am. Chem. Soc.*, 2007, **129**, 5332-5333; (e) Y. Nakao, K. S. Kanyiva and T. Hiyama, *J. Am. Chem. Soc.*, 2008, **130**, 2448-2449; (f) J. Zhou, B. Li, F. Hu and B.-F. Shi, *Org. Lett.*, 2013, **15**, 3460-3463; (g) J. Jin and D. W. C. MacMillan, *Nature*, 2015, **525**, 87-90; (h) S. Yamada, K. Murakami and K. Itami, *Org. Lett.*, 2016, **18**, 2415-2418; (i) Z. Zuo, H. Cong, W. Li, J. Choi, G. C. Fu and D. W. C. MacMillan, *J. Am. Chem. Soc.*, 2016, **138**, 1832-1835.
- 2 For reviews and recent examples: (a) G. W. Rewcastle and A. R. Katritzky, in *Advances in Heterocyclic Chemistry*, ed. R. K. Alan, Academic Press, 1993, vol. 56, pp. 155-302; (b) L.-C. Campeau and K. Fagnou, *Chem. Soc. Rev.*, 2007, **36**, 1058-1068; (c) H. Gao, D. H. Ess, M. Yousufuddin and L. Kürti, *J. Am. Chem. Soc.*, 2013, **135**, 7086-7089; (d) Q.-L. Xu, H. Gao, M. Yousufuddin, D. H. Ess and L. Kürti, *J. Am. Chem. Soc.*, 2013, **135**, 14048-14051.
- 3 (a) D. M. Stout and A. I. Meyers, *Chem. Rev.*, 1982, **82**, 223-243; (b) J. A. Bull, J. J. Mousseau, G. Pelletier and A. B. Charette, *Chem. Rev.*, 2012, **112**, 2642-2713; (c) Z. Pan, X.-J. Qin, Y.-P. Liu, T. Wu, X.-D. Luo and C. Xia, *Org. Lett.*, 2016, **18**, 654-657.
- 4 (a) D. K. Barange, M. T. Johnson, A. G. Cairns, R. Olsson and F. Almqvist, *Org. Lett.*, 2016, **18**, 6228-6231; (b) W. Sun, Z. Xie, J. Liu and L. Wang, *Org. Biomol. Chem.*, 2015, **13**, 4596-4604; (c) D. I. Bugaenko, M. A. Yurovskaya and A. V.

- Karchava, *J. Org. Chem.*, 2017, **82**, 2136-2149; (d) W. Jo, J. Kim, S. Choi and S. H. Cho, *Angew. Chem. Int. Ed.*, 2016, **55**, 9690-9694; (e) X. Chen, S. A. Ruider, R. W. Hartmann, L. González and N. Maulide, *Angew. Chem. Int. Ed.*, 2016, **55**, 15424-15428; (f) B. Yao, R.-J. Song, Y. Liu, Y.-X. Xie, J.-H. Li, M.-K. Wang, R.-Y. Tang, X.-G. Zhang and C.-L. Deng, *Adv. Synth. Catal.*, 2012, **354**, 1890-1896; (g) T. Kato and H. Yamanaka, *J. Org. Chem.*, 1965, **30**, 910-913; (h) R. M. Kellogg and T. J. Van Bergen, *J. Org. Chem.*, 1971, **36**, 1705-1708; (i) P. Schiess and P. Ringele, *Tetrahedron Lett.*, 1972, **13**, 311-312; (j) L.-C. Campeau, S. Rousseaux and K. Fagnou, *J. Am. Chem. Soc.*, 2005, **127**, 18020-18021; (k) H. Andersson, F. Almqvist and R. Olsson, *Org. Lett.*, 2007, **9**, 1335-1337; (l) S. H. Cho, S. J. Hwang and S. Chang, *J. Am. Chem. Soc.*, 2008, **130**, 9254-9256; (m) H. Andersson, M. Gustafsson, D. Boström, R. Olsson and F. Almqvist, *Angew. Chem. Int. Ed.*, 2009, **48**, 3288-3291; (n) H. Andersson, T. Sainte-Luce Banchelin, S. Das, R. Olsson and F. Almqvist, *Chem. Commun.*, 2010, **46**, 3384-3386; (o) F. Zhang and X.-F. Duan, *Org. Lett.*, 2011, **13**, 6102-6105; (p) D. E. Stephens, J. Lakey-Beitia, A. C. Atesin, T. A. Atesin, G. Chavez, H. D. Arman and O. V. Larionov, *ACS Catal.*, 2015, **5**, 167-175.
- 5 (a) K.-y. Akiba, Y. Iseki and M. Wada, *Tetrahedron Lett.*, 1982, **23**, 429-432; (b) D. L. Comins and A. H. Abdullah, *J. Org. Chem.*, 1982, **47**, 4315-4319; (c) D. L. Comins, L. S. King, E. D. Smith and F. C. Février, *Org. Lett.*, 2005, **7**, 5059-5062.
- 6 (a) R. Loska and M. Mąkosza, *J. Org. Chem.*, 2007, **72**, 1354-1365; (b) W. Huang, C. Ni, Y. Zhao, W. Zhang, A. D. Dilman and J. Hu, *Tetrahedron*, 2012, **68**, 5137-5144.
- 7 (a) Q. Chen, X. M. du Jourdin and P. Knochel, *J. Am. Chem. Soc.*, 2013, **135**, 4958-4961; (b) Q. Chen, T. Leon and P. Knochel, *Angew. Chem. Int. Ed.*, 2014, **53**, 8746-8750.
- 8 (a) J. Ryu, S. H. Cho and S. Chang, *Angew. Chem. Int. Ed.*, 2012, **51**, 3677-3681; (b) Y. Nakao, Y. Yamada, N. Kashiwara and T. Hiyama, *J. Am. Chem. Soc.*, 2010, **132**, 13666-13668; (c) Y. Nakao, *Synthesis*, 2011, **2011**, 3209-3219.
- 9 (a) I. Thomé and C. Bolm, *Org. Lett.*, 2012, **14**, 1892-1895; (b) P. Quinio, D. S. Roman, T. León, S. William, K. Karaghiosoff and P. Knochel, *Org. Lett.*, 2015, **17**, 4396-4399; (c) R.-J. Tang, L. Kang and L. Yang, *Adv. Synth. Catal.*, 2015, **357**, 2055-2060; (d) A. P. Antonchick and L. Burgmann, *Angew. Chem. Int. Ed.*, 2013, **52**, 3267-3271; (e) G. Deng, K. Ueda, S. Yanagisawa, K. Itami and C.-J. Li, *Chem. Eur. J.*, 2009, **15**, 333-337; (f) X. Li, H.-Y. Wang and Z.-J. Shi, *New J. Chem.*, 2013, **37**, 1704-1706.
- 10 J. Xu, L.-D. Shao, D. Li, X. Deng, Y.-C. Liu, Q.-S. Zhao and C. Xia, *J. Am. Chem. Soc.*, 2014, **136**, 17962-17965.
- 11 For recent examples: (a) Q.-Y. Meng, J.-J. Zhong, Q. Liu, X.-W. Gao, H.-H. Zhang, T. Lei, Z.-J. Li, K. Feng, B. Chen, C.-H. Tung and L.-Z. Wu, *J. Am. Chem. Soc.*, 2013, **135**, 19052-19055; (b) X.-B. Li, Z.-J. Li, Y.-J. Gao, Q.-Y. Meng, S. Yu, R. G. Weiss, C.-H. Tung and L.-Z. Wu, *Angew. Chem. Int. Ed.*, 2014, **53**, 2085-2089; (c) J.-J. Zhong, Q.-Y. Meng, B. Liu, X.-B. Li, X.-W. Gao, T. Lei, C.-J. Wu, Z.-J. Li, C.-H. Tung and L.-Z. Wu, *Org. Lett.*, 2014, **16**, 1988-1991; (d) X.-W. Gao, Q.-Y. Meng, J.-X. Li, J.-J. Zhong, T. Lei, X.-B. Li, C.-H. Tung and L.-Z. Wu, *ACS Catal.*, 2015, **5**, 2391-2396; (e) M. Xiang, Q.-Y. Meng, J.-X. Li, Y.-W. Zheng, C. Ye, Z.-J. Li, B. Chen, C.-H. Tung and L.-Z. Wu, *Chem. Eur. J.*, 2015, **21**, 18080-18084; (f) G. Zhang, C. Liu, H. Yi, Q. Meng, C. Bian, H. Chen, J.-X. Jian, L.-Z. Wu and A. Lei, *J. Am. Chem. Soc.*, 2015, **137**, 9273-9280; (g) K.-H. He and Y. Li, *ChemSusChem*, 2014, **7**, 2788-2790; (h) A.-X. Zhou, L.-L. Mao, G.-W. Wang and S.-D. Yang, *Chem. Commun.*, 2014, **50**, 8529-8532; (i) K. Luo, Y.-Z. Chen, W.-C. Yang, J. Zhu and L. Wu, *Org. Lett.*, 2016, **18**, 452-455.
- 12 (a) M. Wills, in *Hydrogen Transfer Reactions: Reductions and Beyond*, eds. G. Guillena and D. J. Ramón, Springer International Publishing, Cham, 2016, pp. 69-104; (b) S.-Y.

Journal Name

ARTICLE

- 1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
- Zhang, F.-M. Zhang and Y.-Q. Tu, *Chem. Soc. Rev.*, 2011, **40**, 1937-1949; (c) J. S. M. Samec, J.-E. Backvall, P. G. Andersson and P. Brandt, *Chem. Soc. Rev.*, 2006, **35**, 237-248.
- 13 (a) R. P. Herrera, in *Hydrogen Transfer Reactions: Reductions and Beyond*, eds. G. Guillena and D. J. Ramón, Springer International Publishing, Cham, 2016, pp. 106-125; (b) C. Zhu, K. Saito, M. Yamanaka and T. Akiyama, *Acc. Chem. Res.*, 2015, **48**, 388-398; (c) F. Shi and L.-Z. Gong, *Angew. Chem. Int. Ed.*, 2012, **51**, 11423-11425; (d) C. Zheng and S.-L. You, *Chem. Soc. Rev.*, 2012, **41**, 2498-2518; (e) U. Eisner and J. Kuthan, *Chem. Rev.*, 1972, **72**, 1-42; (f) C. E. Paul, I. W. C. E. Arends and F. Hollmann, *ACS Catal.*, 2014, **4**, 788-797; (g) T. J. Van Bergen, T. Mulder, R. A. Van Der Veen and R. M. Kellogg, *Tetrahedron*, 1978, **34**, 2377-2383.
- 14 M. M. Hashemi, H. Ghafuri and Z. Karimi-Jaberi, *Monatsh. Chem.*, 2006, **137**, 197-200.