Visible-Light-Promoted Conversion of Alkyl Benzyl Ether to Alkyl Ester or Alcohol via O-α-sp³ C−H Cleavage

Ping Lu, Tianyuan Hou, Xiangyong Gu, and Pixu Li*

Key Laboratory of Organic Synthesis of Jiangsu Province, College of Chemistry, Chemical Engineering, and Materials Science, Soochow University, 199 RenAi Road, Suzhou, Jiangsu 215123, China

S *Supporting Information*

ABSTRACT: A mild and high-yielding visible-light-promoted conversion of alkyl benzyl ethers to the alkyl esters or alkyl alcohols was developed. Mechanistic studies provided evidence for a radical chain reaction involving the homolytic cleavage of *O-α-sp³* C−H bonds in the substrate as one of the propagation steps. We propose that α-bromoethers are key intermediates in the transformation.
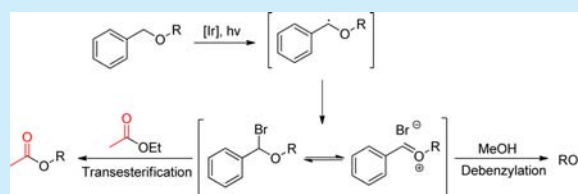
The research on the cleavage of an inert sp³ C−H bond adjacent to heteroatoms has attracted interest from the organic chemistry community.[1] One of the general activation modes is the oxidation of a heteroatom to the corresponding radical cation, which activates the adjacent C−H bond. The reactions involving *N-α-sp³* C−H bond cleavage often go through this pathway.[2] However, this strategy is hardly applicable to the cleavage of an *O-α-sp³* C−H bond presumably due to the high electronegativity of the O-atom. As a result, the chemistry involving the cleavage of the *O-α-sp³* C−H bond remains underdeveloped.[3]

Ir/Ru polypyridyl complex catalyzed reactions under visible light irradiation have emerged as a powerful tool in redox chemistry.[4] Many reports of visible-light-promoted *N-α-sp³* C−H bond cleavage have appeared in the literature because amine nitrogen could be oxidized by a number of sensitizers.[5,6] In contrast, the cleavage of the C−H bond adjacent to an O-atom under visible light conditions is rarely reported, presumably due to the above-mentioned difficulty in the oxidation of oxygen lone pairs. Stephenson et al. took advantage of the relatively low oxidation potential of the *p*-methoxyphenyl (PMP) group and developed an elegant visible-light-mediated deprotection protocol of PMB ether.[7] However, this protocol cannot be applied to the benzyl ether because an electron-rich PMP group is required. MacMillan et al. reported a visible-light-mediated *O-α-sp³* C−H bond cleavage using a thiyl radical to abstract benzylic hydrogen, followed by the combination of the benzylic radical with a *p*-dicyanobenzene radical anion or imine to form new C−C bond.[8] Very recently, the same research group reported a photoredox direct α-arylation of ether using a sulfate radical to activate the C−H bond in ether.[9] In continuation of our interest in the activation of the sp³ C−H bond adjacent to the heteroatom,[10] we envisioned that a practical activation mode for ether to participate in a visible-light-promoted photoredox reaction would go through a hydrogen atom transfer (HAT) process. We postulated that HAT from alkyl benzyl ether to electrophilic species such as a trichloromethyl radical would afford a benzyl radical. Facile single-electron oxidation of the benzyl radical
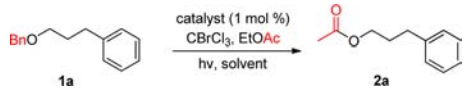
would result in the formation of an oxacarbenium ion. Consequently, new chemistry could be developed by taking advantage of the reactive oxacarbenium ion or its related species. The reactions involving the oxacarbenium ion via hydride abstraction of benzyl ethers or allyl ethers using an oxoammonium salt have been reported by Bobbitt,[11] Bailey,[12] Leadbeater,[13] and Garcia-Mancheño[14] recently. Herein, we present a visible-light-promoted direct conversion of alkyl benzyl ether to alkyl ester or alcohol initiated by *O-α-sp³* C−H bond cleavage (Scheme 1).

Scheme 1. Photoredox Reactions of *O-α-sp³* C−H Cleavage
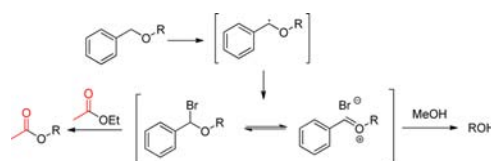
Our investigation of new visible-light-mediated reactions of ether used benzyl ether as the model substrate since the homolytic fission of benzylic C−H bond affords a stable benzylic radical. The oxidation of the benzylic radical of ether by visible-light-excited sensitizer is likely to occur due to the formation of a stable phenyl oxonium ion. We initiated our study by examining the photochemical oxidation of (3-(benzyloxy)propyl)benzene (**1a**) in the presence of CBrCl₃. However, a messy reaction was observed after irradiating the reaction mixture under a 14 W compact fluorescent light for 12 h (Table 1, entry 1). To our surprise, addition of EtOAc to the reaction mixture upon disappearance of **1a** afforded 3-phenylpropyl acetate (**2a**) in 99% yield (Table 1, entry 2). Ethyl acetate was then used as a reagent in the reaction (Table 1, entries 3−7). It turned out that 20 equiv of ethyl acetate were necessary to afford **2a** in good yield.

Table 1. Optimization of the Reaction Conditions[a]
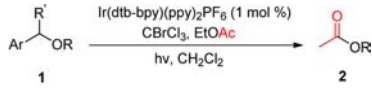
entry	catalyst	solvent	EtOAc (equiv)	GC yield
1	Ir(dtb-bpy)(ppy)$_2$PF$_6$	CH$_2$Cl$_2$	–	messy
2	Ir(dtb-bpy)(ppy)$_2$PF$_6$	CH$_2$Cl$_2$	–	99%[b]
3	Ir(dtb-bpy)(ppy)$_2$PF$_6$	CH$_2$Cl$_2$	1	21%
4	Ir(dtb-bpy)(ppy)$_2$PF$_6$	CH$_2$Cl$_2$	2	30%
5	Ir(dtb-bpy)(ppy)$_2$PF$_6$	CH$_2$Cl$_2$	5	60%
6	Ir(dtb-bpy)(ppy)$_2$PF$_6$	CH$_2$Cl$_2$	10	77%
7	Ir(dtb-bpy)(ppy)$_2$PF$_6$	CH$_2$Cl$_2$	20	99%
8	Ir(ppy)$_3$	CH$_2$Cl$_2$	20	N.R.
9	FIrpic	CH$_2$Cl$_2$	20	N.R.
10	Ru(bpy)$_3$Cl$_2$·6H$_2$O	CH$_2$Cl$_2$	20	N.R.
11	Ru(ppy)$_3$(PF$_6$)$_2$	CH$_2$Cl$_2$	20	N.R.
12	Ir(dtb-bpy)(ppy)$_2$PF$_6$	DMSO	20	N.R.
13	Ir(dtb-bpy)(ppy)$_2$PF$_6$	DMF	20	N.R.
14	Ir(dtb-bpy)(ppy)$_2$PF$_6$	MeCN	20	7%
15	Ir(dtb-bpy)(ppy)$_2$PF$_6$	HCCl$_3$	20	20%
16	Ir(dtb-bpy)(ppy)$_2$PF$_6$	CH$_2$ClCH$_2$Cl	20	5%
17	–	CH$_2$Cl$_2$	20	trace
18	Ir(dtb-bpy)(ppy)$_2$PF$_6$, no light	CH$_2$Cl$_2$	20	trace

[a]Reactions were performed with **1a** (0.5 mmol), CBrCl$_3$ (1.0 mmol), EtOAc, and catalyst (1 mol %) in solvent (2 mL), irradiated under 14 W CFL for 12 h at rt. [b]EtOAc was added after the starting material had been consumed.

Ru(bpy)$_3$Cl$_2$·6H$_2$O, Ru(ppy)$_3$(PF$_6$)$_2$, Ir(ppy)$_3$, and Bis[2-(4,6-difluorophenyl)pyridinato-C^2,N](picolinato)iridium(III) (FIrpic) were found to be ineffective (Table 1, entries 8−11). A survey of solvents demonstrated that CH$_2$Cl$_2$ was the optimal solvent for this reaction (Table 1, entries 12−16). In the absence of light or catalyst, only a trace amount of product was obtained, indicating the reaction is a visible-light-promoted reaction (Table 1, entries 17−18).
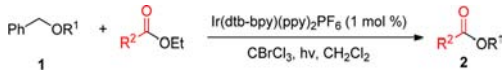
Typically, the conversion of benzyl ether to the corresponding acetate requires two separate steps, hydrogenolysis of benzyl ether to afford alcohol and a subsequent esterification reaction. The direct conversion from alkyl benzyl ether to alkyl ester using an alkyl acetate as the reagent has never been reported in the literature. Therefore, substrate scope investigation and mechanistic study are warranted. First, we explored the scope of different ethers (Table 2). Excellent yields were generally obtained for different alkyl benzyl ethers (Table 2, entries 1−7). The benzylic C−H adjacent to the O-atom is selectively cleaved over the normal benzylic C−H bond, including the benzylic C−H bond of the *p*-methoxyphenyl group. Alkyl benzyl ether bearing a bromo group at the alkyl chain was found to afford the corresponding product in high yield too (Table 2, entry 8, 95%). Substituents, such as methyl and halides, at the benzene ring were all tolerated and afforded the corresponding products in good yields (Table 2, entries 9−12). However, secondary benzyl ether with a methyl or phenyl group at the benzylic position gave lower yields (Table 2, entries 13 and 14), probably due to the steric effect.

Next, we turned our attention to the reaction with different esters, as this would lead to different ester products. Various alkyl carboxylic acid esters participated in the reactions forming the corresponding esters in good yields (Table 3, entries 1−4).

Table 2. Substrate Scope Screening[a]

entry	substrate	product	yield[b]
1	1a	2a	91%
2	1b	2b	96%
3	1c	2c	84%
4	1d	2d	99%
5	1e	2e	94%
6	1f	2f	97%
7	1g	2g	94%
8	1h	2h	95%
9	1i	2a	93%
10	1j	2a	92%[c]
11	1k	2a	93%[c]
12	1l	2a	95%[c]
13	1m	2a	70%
14	1n	2a	50%

[a]Reaction conditions: substrate **1** (0.5 mmol), Ir(dtb-bpy)(ppy)$_2$PF$_6$ (1 mol %), CBrCl$_3$ (1.0 mmol), and EtOAc (10 mmol) in CH$_2$Cl$_2$ (2 mL), irradiated under 14 W CFL for 12 h at rt. [b]Isolated yield. [c]Reacted for 24 h.

Table 3. Transesterification with Different Esters[a]

entry	substrate	additive	product	yield[b]
1	1a		2i	99%
2	1a		2j	86%
3	1a		2k	87%
4	1g		2l	89%
5	1a		3a	64%[c]

[a]Reaction conditions: **1a** or **1g** (0.5 mmol), Ir(dtb-bpy)(ppy)$_2$PF$_6$ (1 mol %), CBrCl$_3$ (1.0 mmol), and ester (10 mmol) in CH$_2$Cl$_2$ (2 mL), irradiated under 14 W CFL for 12 h at rt. [b]Isolated yield. [c]Isolated yield of **3a**.

However, ethyl benzoate did not undergo transesterification reaction. Only 3-phenyl-1-propanol was isolated in 64% yield (Table 3, entry 5).

We then began the study to understand the reaction mechanism. First, the initiation of the reaction was investigated using a fluorescence quenching experiment. The results (see

Supporting Information) showed that CBrCl$_3$ is much more efficient in quenching the visible-light-excited Ir(dtb-bpy)-(ppy)$_2$PF$_6$, indicating that an oxidative quenching of the excited catalyst by CBrCl$_3$ afforded the Br$^-$ anion and ·CCl$_3$ radical. The resulting ·CCl$_3$ radical should be responsible for the abstraction of the H-atom from (3-(benzyloxy)propyl)benzene to give the corresponding benzylic radical. Indeed, chloroform was formed as a stoichiometric product by in situ NMR monitoring. This result is consistent with the report by Stephenson et al.[7] Next, it is important to answer what happened to the benzylic radical. In situ ^{1}H NMR spectra of the reactions of **1a** and **1a-d_2** (the two benzylic hydrogens in **1a** were replaced by deuteriums) performed in CD$_2$Cl$_2$ in the absence of EtOAc showed that a distinctive proton signal at 6.98 ppm increased as the reaction of **1a** proceeded. No such signal was observed in the reaction of **1a-d_2** (Figure 1, eqs 1 and 2). The chemical shift of the benzylic
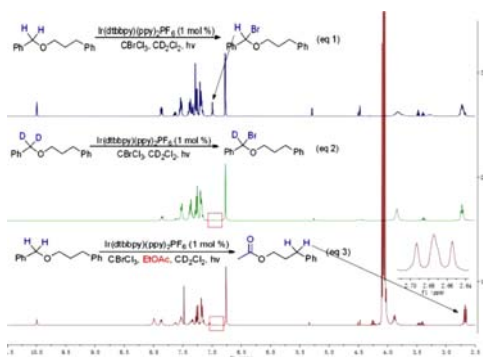

Figure 1. NMR study.

proton adjacent to the O-atom in an oxonium ion should be further downfield than 6.98 ppm. Therefore, this proton signal was attributed to α-bromoether. In the reaction with EtOAc (Figure 1, eq 3), the 6.98 ppm signal could not be seen because the α-bromoether intermediate was converted to the product **2a**.

The α-bromoether could be formed via two possible pathways: (1) the benzylic radical is oxidized to an oxonium ion, followed by nucleophilic addition of the Br$^-$ anion formed in the oxidative quenching step; or (2) the benzylic radical abstracts a bromine atom from CBrCl$_3$ to form the α-bromoether, to generate a new ·CCl$_3$ radical. The former pathway would be a radical-ionic crossover pathway which relies on continuous irradiation. In contrast, the latter pathway is a radical chain propagation pathway. Therefore, a light on/off switch experiment was performed (see Supporting Information). The reaction of **1a** did not stop completely in the absence of light. Instead, the product **2a** kept forming after turning off the light. So the radical chain propagation mechanism probably is operative in the reaction. It is one of the few Ru/Ir complex-catalyzed visible-light-promoted radical chain reactions.

It was important to find out the role of ester and how the acyl group was transferred. In the reaction of dodecyl acetate, dodecanol was observed as one of the products (Scheme 2, eq 1). In the reaction using S-ethyl thioacetate, (phenylmethylene)bis-(ethylsulfane) (**8**) was formed along with 57% of benzaldehyde and 97% of the product **2a** (Scheme 2, eq 2). In contrast, O-ethyl thioacetate was unreactive in otherwise identical reaction conditions. The results showed that the sp^3 O-atom of ester **2a** was from the ether **1a**, indicating that the reaction might go through a tetrahedral intermediate by nucleophilic addition to ester instead of a nucleophilic addition of caboxylate to an

Scheme 2. Investigations of the Role of Ester
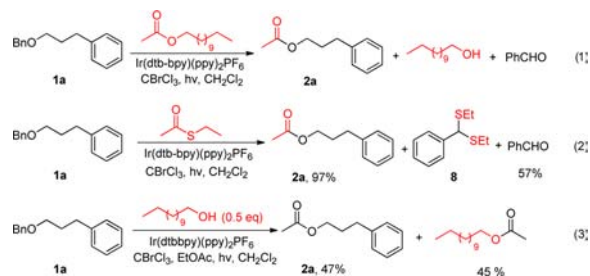
oxonium ion generated from benzyl ether. When substrate **1a** and 0.5 equiv of dodecan-1-ol were subjected to the standard conditions, both **2a** and dodecyl acetate were observed in the product mixture (Scheme 2, eq 3). This result suggested alcohol might be one of the key intermediates in the reaction pathway.

On the basis of the above-mentioned results, a reaction mechanism was proposed in Scheme 3. The reaction is initiated

Scheme 3. Proposed Mechanism
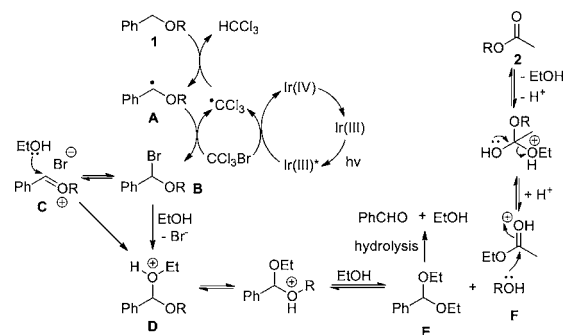
via the oxidative quenching of Ir(III)* by BrCCl$_3$ to afford a ·CCl$_3$ radical, which abstracts a H-atom from benzyl ether **6** to form chloroform and benzylic radical **A**. In the radical chain propagation step, the resulting benzylic radical abstracts a Br-atom from BrCCl$_3$ to give the corresponding α-bromoether **B** and regenerates the ·CCl$_3$ radical. Next, a nucleophilic attack of residual alcohol in ethyl acetate to either the α-bromoether **B** or oxonium bromide **C** affords the mixed acetal **D**. Proton transfer and a second nucleophilic attack of alcohol afford benzaldehyde diethyl acetal (**E**) and alcohol **F**. Alcohol **F** then undergoes transesterification with excess ethyl acetate to afford the final product **2**. Alternatively, the conversion of **B** to **2** could be triggered by a trace amount of water in solvent or EtOAc in a similar manner.

Given the reaction pathway works as proposed, it could be anticipated that debenzylation would occur in the absence of ethyl acetate. So we investigated the reaction using alcohol to replace ester. The reaction was completely shut down with the addition of MeOH as a reagent in the reaction. Therefore, MeOH was added after the reaction mixture was irradiated under visible light for 12 h. To our delight, alcohol **3a** was obtained in 85% isolated yield. A small amount of alkyl bromide was observed as the byproduct. This reaction is an alternative, mild method for benzyl ether deprotection when hydrogenolysis is not compatible with other functionalities in a complex molecule. A series of benzyl ethers were screened, and the results were summarized in Table 4. Benzyl ethers of primary and secondary alcohols afforded the corresponding products with reasonably good isolated yields.

Table 4. Substrate Scope for the Debenzylation Reaction[a]

entry	substrate	product	yield [b]
1	1a	3a	82% (85%)
2	1b	3b	67%
3	1c	3c	69%
4	1g	3d	66%
5	1o	3e	40% (78%)
6	1p	3f	76%
7	1n	3a	73%

[a]Reaction conditions: substrate **1** (0.5 mmol), Ir(dtb-bpy)(ppy)$_2$PF$_6$ (1 mol %), and CBrCl$_3$ (1.0 mmol) in CH$_2$Cl$_2$ (2 mL), irradiated under 14 W CFL at rt. MeOH (10 mL) was added after 12 h. [b]Isolated yield; GC yield in parentheses.

In conclusion, a visible-light-mediated *O*-α-sp^3 C−H cleavage strategy was developed. Oxidative quenching of photoexcited Ir(dtb-bpy)(ppy)$_2$PF$_6$ with BrCCl$_3$ generates the electron-deficient ·CCl$_3$ radical, which abstracts the benzylic hydrogen of alkyl benzyl ether and triggers radical chain propagation of the benzylic radical with BrCCl$_3$ to form a reactive α-bromoether intermediate. The transesterification of the α-bromoether with excess ester affords alkyl ester. This mild and high-yielding reaction is a convenient alternative route to the traditional transformations of alkyl benzyl ether to the corresponding alkyl ester via a two-step hydrogenolysis and esterification procedure. In addition, by replacing the ester reactant with MeOH, a visible-light-promoted debenzylation reaction was developed. Mechanistic study showed that the reaction is an iridium-initiated photocatalytic radical chain propagation reaction.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Experimental procedures, characterization data, and ^{1}H and ^{13}C NMR spectra for all products. This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: lipixu@suda.edu.cn.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

■ REFERENCES

(1) (a) Li, C.-J. *Acc. Chem. Res.* **2009**, *42*, 335. (b) Baudoin, O. *Chem. Soc. Rev.* **2011**, *40*, 4902. (c) Chiba, S.; Chen, H. *Org. Biomol. Chem.* **2014**, *12*, 4051. (d) Xie, J.; Pan, C.; Abdukader, A.; Zhu, C. *Chem. Soc. Rev.* **2014**, *43*, 5245.

(2) (a) Campos, K. R. *Chem. Soc. Rev.* **2007**, *36*, 1069. (b) Mitchell, E. A.; Peschiulli, A.; Lefevre, N.; Meerpoel, L.; Maes, B. U. W. *Chem.—Eur. J.* **2012**, *18*, 10092. (c) Li, Y.; Ma, L.; Li, Z. *Chin. J. Org. Chem.* **2013**, *33*, 704.

(3) Zhang, S.-Y.; Zhang, F.-M.; Tu, Y.-Q. *Chem. Soc. Rev.* **2011**, *40*, 1937.

(4) (a) Hari, D. P.; Koenig, B. *Chem. Commun.* **2014**, *50*, 6688. (b) Xi, Y.; Yi, H.; Lei, A. *Org. Biomol. Chem.* **2013**, *11*, 2387. (c) Zeitler, K. *Angew. Chem., Int. Ed.* **2009**, *48*, 9785. (d) Yoon, T. P.; Ischay, M. A.; Du, J. *Nat. Chem.* **2010**, *2*, 527. (e) Narayanam, J. M. R.; Stephenson, C. R. J. *Chem. Soc. Rev.* **2011**, *40*, 102. (f) Teplý, F. *Collect. Czech. Chem. Commun.* **2011**, *76*, 859. (g) Xuan, J.; Xiao, W.-J. *Angew. Chem., Int. Ed.* **2012**, *51*, 6828. (h) Ravelli, D.; Fagnoni, M.; Albini, A. *Chem. Soc. Rev.* **2013**, *42*, 97. (i) Schultz, D. M.; Yoon, T. P. *Science* **2014**, *343*, 985. (j) Prier, C. K.; Rankic, D. A.; MacMillan, D. W. C. *Chem. Rev.* **2013**, *113*, 5322. (k) Tucker, J. W.; Stephenson, C. R. J. *J. Org. Chem.* **2012**, *77*, 1617.

(5) (a) Xie, J.; Jin, H.; Xu, P.; Zhu, C. *Tetrahedron Lett.* **2014**, *55*, 36. (b) Shi, L.; Xia, W. *Chem. Soc. Rev.* **2012**, *41*, 7687. (c) Hu, J.; Wang, J.; Nguyen, T. H.; Zheng, N. *Beilstein J. Org. Chem.* **2013**, *9*, 1977.

(6) (a) Pandey, G.; Jadhav, D.; Tiwari, S. K.; Singh, B. *Adv. Synth. Catal.* **2014**, *356*, 2813. (b) Dai, X.; Cheng, D.; Guan, B.; Mao, W.; Xu, X.; Li, X. *J. Org. Chem.* **2014**, *79*, 7212. (c) Miyake, Y.; Ashida, Y.; Nakajima, K.; Nishibayashi, Y. *Chem.—Eur. J.* **2014**, *20*, 6120. (d) Dai, X.-J.; Xu, X.-L.; Cheng, D.-P.; Li, X.-N. *Chin. Chem. Lett.* **2014**, *25*, 545. (e) Ushakov, D. B.; Gilmore, K.; Kopetzki, D.; McQuade, D. T.; Seeberger, P. H. *Angew. Chem., Int. Ed.* **2014**, *53*, 557. (f) Yoo, W.-J.; Kobayashi, S. *Green Chem.* **2014**, *16*, 2438. (g) Bergonzini, G.; Schindler, C. S.; Wallentin, C.-J.; Jacobsen, E. N.; Stephenson, C. R. J. *Chem. Sci.* **2014**, *5*, 112. (h) Wei, W.-t.; Dong, X.-j.; Nie, S.-z.; Chen, Y.-y.; Zhang, X.-j.; Yan, M. *Org. Lett.* **2013**, *15*, 6018. (i) Singh, A.; Arora, A.; Weaver, J. D. *Org. Lett.* **2013**, *15*, 5390. (j) Zhang, P.; Xiao, T.; Xiong, S.; Dong, X.; Zhou, L. *Org. Lett.* **2014**, *16*, 3264. (k) Noble, A.; MacMillan, D. W. C. *J. Am. Chem. Soc.* **2014**, *136*, 11602. (l) Nakajima, K.; Kitagawa, M.; Ashida, Y.; Miyake, Y.; Nishibayashi, Y. *Chem. Commun.* **2014**, *50*, 8900. (m) Gao, X.-W.; Meng, Q.-Y.; Xiang, M.; Chen, B.; Feng, K.; Tung, C.-H.; Wu, L.-Z. *Adv. Synth. Catal.* **2013**, *355*, 2158. (n) Zhu, S.; Das, A.; Bui, L.; Zhou, H.; Curran, D. P.; Rueping, M. *J. Am. Chem. Soc.* **2013**, *135*, 1823. (o) Rueping, M.; Vila, C. *Org. Lett.* **2013**, *15*, 2092. (p) Mathis, C. L.; Gist, B. M.; Frederickson, C. K.; Midkiff, K. M.; Marvin, C. C. *Tetrahedron Lett.* **2013**, *54*, 2101. (q) Espelt, L. R.; Wiensch, E. M.; Yoon, T. P. *J. Org. Chem.* **2013**, *78*, 4107. (r) Xie, J.; Xue, Q.; Jin, H.; Li, H.; Cheng, Y.; Zhu, C. *Chem. Sci.* **2013**, *4*, 1281. (s) Zhu, S.; Rueping, M. *Chem. Commun.* **2012**, *48*, 11960. (t) Rueping, M.; Vila, C.; Szadkowska, A.; Koenigs, R. M.; Fronert, J. *ACS Catal.* **2012**, *2*, 2810. (u) Miyake, Y.; Nakajima, K.; Nishibayashi, Y. *Chem.—Eur. J.* **2012**, *18*, 16473. (v) To, W.-P.; Liu, Y.; Lau, T.-C.; Che, C.-M. *Chem.—Eur. J.* **2013**, *19*, 5654. (w) Miyake, Y.; Nakajima, K.; Nishibayashi, Y. *J. Am. Chem. Soc.* **2012**, *134*, 3338.

(7) Tucker, J. W.; Narayanam, J. M. R.; Shah, P. S.; Stephenson, C. R. J. *Chem. Commun.* **2011**, *47*, 5040.

(8) (a) Qvortrup, K.; Rankic, D. A.; MacMillan, D. W. C. *J. Am. Chem. Soc.* **2013**, *136*, 626. (b) Hager, D.; MacMillan, D. W. C. *J. Am. Chem. Soc.* **2014**, *136*, 16986.

(9) Jin, J.; MacMillan, D. W. C. *Angew. Chem., Int. Ed.* **2015**, *54*, 1565.

(10) (a) Zhou, H.; Lu, P.; Gu, X.; Li, P. *Org. Lett.* **2013**, *15*, 5646. (b) Li, X.; Gu, X.; Li, Y.; Li, P. *ACS Catal.* **2014**, *4*, 1897.

(11) (a) Bobbitt, J. M.; Eddy, N. A.; Richardson, J. J.; Murray, S. A.; Tilley, L. J. *Org. Synth.* **2013**, *90*, 215. (b) Leadbeater, N. E.; Bobbitt, J. M. *Aldrichimica Acta* **2014**, *47*, 65.

(12) Pradhan, P. P.; Bobbitt, J. M.; Bailey, W. F. *J. Org. Chem.* **2009**, *74*, 9524.

(13) Kelly, C. B.; Ovian, J. M.; Cywar, R. M.; Gosselin, T. R.; Wiles, R. J.; Leadbeater, N. E. *Org. Biomol. Chem.* **2015**, *13*, 4255.

(14) (a) Richter, H.; Mancheno, O. G. *Eur. J. Org. Chem.* **2010**, 4460. (b) Richter, H.; Rohlmann, R.; Mancheno, O. G. *Chem.—Eur. J.* **2011**, *17*, 11622.