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N-Bromosuccinimide (NBS)-Catalyzed C−H Bond Functionalization: An Annulation of Alkynes with Electron Withdrawing Group (EWG)-Substituted Acetyl Indoles for the Synthesis of Carbazoles

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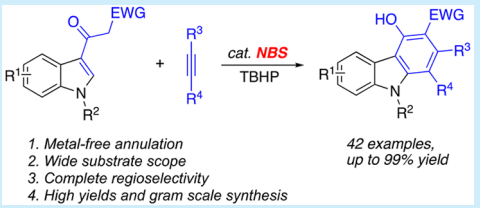
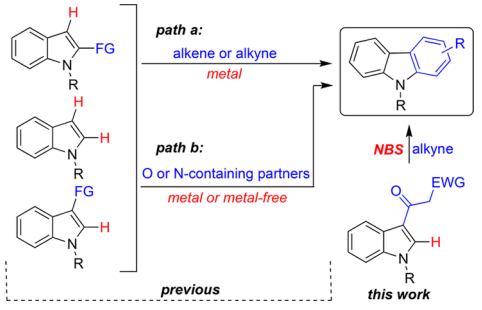
Supporting Information

ABSTRACT: An *N*-bromosuccinimide-catalyzed intermolecular annulation of acetyl indoles with alkynes was developed, allowing for regioselective formation of valuable carbazoles through direct C−H bond functionalization. The readily available catalyst, wide substrate scope, gram scale synthesis, and mild conditions make this method practical. Mechanistic investigations indicate that the bromination of acetyl indole takes place to generate a bromide intermediate, followed by coupling with an alkyne and intramolecular cycloaromatization to furnish carbazole products.



The wealth of carbazoles in biologically active molecules[1] and organic light-emitting materials[2] has driven organic chemists to continue developing novel methods toward their synthesis. Apart from the traditional Fischer−Borsche,[3] Bucherer,[4] Cadogan,[5] and Graebe−Ullmann[6] carbazole synthesis, recent work has enabled carbazole construction to be performed with a growing number of starting materials.[7] Of these processes, intermolecular annulation has received much attention because it allows for the atom-economical synthesis of functionalized carbazoles directly from simple indole or its easily available C2(3)-functionalized derivatives (Scheme 1). The benzannulation of indoles typically occurs by two pathways in terms of the reaction partner used. The first proceeds through transition-metal-catalyzed C−H bond activation of indoles and their reaction partners alkenes or alkynes (***path a***). Transition metal catalysts such as Pd,[8] Au,[9] Ag,[10] Ir,[11] Mn,[12] bimetallic Pd−Cu,[13] and trimetallic Pd−Cu−Ag[14] were revealed to catalyze these [4 + 2] or [2 + 2 + 2] cycloadditions to produce various carbazoles. The second proceeds via tandem reaction of indoles with diene or alkene precursors to furnish the carbazoles (***path b***).[15] This strategy employs a variety of O- or N-containing compounds as reaction partners to generate intermediates of cyclization. Although some elegant metal-free examples have been reported,[15f−p] these reactions are often accompanied by the loss of large molecular fragments, and some of them are actually one-pot multistep reactions rather than one-step transformations. The preparation of some unusual starting materials is needed in certain cases of ***path b***. By comparison, ***path a*** is a more efficient cyclization strategy with higher atom economy since it is based on the direct cross-dehydrogenative coupling (CDC) reaction of multiple C−H bonds.[16] Another advantage of ***path a*** is that various functionalized alkenes or alkynes are readily available. Thus, replacement of metal catalysts to common organic catalysts will make this approach more attractive. Very recently, simple iodine reagents such as molecular iodine and iodide salts have been intensively studied as an environmentally friendly alternative to metal catalysts in C−H bond functionalization.[17] In sharp contrast, many cheap and readily available bromine reagents are well-known for their bromination and oxidation reactions,[18] but their catalytic applications in organic synthesis,[19] especially in the direct C−H bond functionalization for C−C bond formation, are extremely rare.[19f] Herein, we report an *N*-bromosuccinimide (NBS) catalyzed intermolecular annulation of functionalized indoles with alkynes through direct C−H bond functionalization (Scheme 1). This highly efficient and practical method allows for the gram scale synthesis of carbazoles with complete regioselectivity under mild conditions, providing a useful alternative to existing protocols.

Scheme 1. Annulation for Synthesis of Carbazoles



The study began by investigating the reaction of 3-(1*H*-indol-3-yl)-3-oxopropanenitrile **1a** with phenylacetylene **2a** using TBHP

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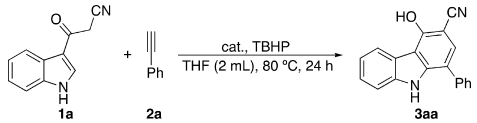
Table 1. Screening of the Reaction Conditions[a]



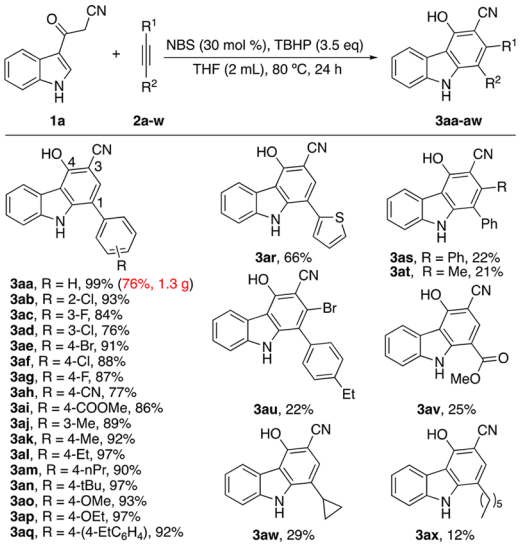
entry	cat. (x mol %)	yield (%)
1	Bu_4NI (10)	trace
2	KI (10)	trace
3	I_2 (10)	24
4	Bu_4NBr (10)	16
5	NBS (10)	66
6	NBS (30)	90
7[b]	NBS (30)	99
8[b]	–	trace

[a]Reaction conditions: **1a** (0.5 mmol), **2a** (1.0 mmol), TBHP (3.0 equiv, 70% aqueous solution), under air; isolated yields. [b]TBHP (3.5 equiv, 70% aqueous solution).

as an oxidant. Attempts to realize the intermolecular annulation using 10 mol % of Bu_4NI or KI only led to a trace amount of the desired product **3aa** (Table 1, entries 1 and 2), while I_2 led to **3aa** in 24% isolated yield (entry 3), accompanied by the oxyiodination of alkyne **2a**, which converted to a complex mixture of side products.[20] Considering that bromide (Br^-) has a higher oxidation potential than iodide (I^-),[21] we then used bromides instead of iodides to avoid the side reactions. However, no yield improvement was observed with Bu_4NBr (entry 4). We were delighted to find that NBS could promote the annulation with high catalytic efficacy to afford **3aa** in 66% yield (entry 5). Increasing the amount of NBS to 30 mol % gave a very high yield (90%) of **3aa** (entry 6), and a quantitative yield was further achieved in the presence of 3.5 equiv of TBHP (entry 7). It is worth mentioning that the annulation of **1a** and **2a** yielded only trace product **3aa** in the absence of NBS (entry 8).

Encouraged by the excellent yield, we further performed the annulation in gram scale under the optimal conditions, and 1.3 g of **3aa** was isolated in 76% yield starting from 1.5 g of **1a** and 0.4 g of **2a** (Scheme 2, **3aa**). Moreover, this operationally simple cycloaromatization reaction installs a cyano group at C3 and a hydroxyl at C4, which provides the possibility of modifying carbazoles. With the established conditions in hand, various alkynes were first investigated to explore the applicability of the reaction. As shown in Scheme 2, an array of diversely substituted terminal arylacetylenes underwent the annulations to afford the corresponding carbazoles **3aa**–**aq** in good to excellent yields. More than half of them afforded the yields over 90%, and even several alkynes gave almost quantitative yields (Scheme 2, **3aa**, **3al**, **3an**, and **3ap**). As is known, the use of terminal alkynes in the transition-metal-catalyzed annulation is often problematic due to the homocoupling. Furthermore, some annulations produced a mixture of regioisomers without selectivity when unsymmetrical alkynes were used as reaction partners. The present metal-free process avoids the homocoupling of these terminal alkynes and leads to a completely regioselective construction of carbazole in which the aryl group is located at the C1 position. For product **3al**, its constitution was unambiguously established by single-crystal X-ray analyses.[22] The reaction conditions could also be extended to the regioselective formation of a thiophene substituted carbazole in 66% yield, using 2-ethynylthiophene **2r** (Scheme 2, **3ar**). Unfortunately, the low yields were observed in the reactions of internal alkynes (**3as**–**au**). The annulation of 1-bromo-2-phenylacetylene **2u** yields a carbazole bromide **3au** that can be

Scheme 2. Variation of the Alkyne Component[a]

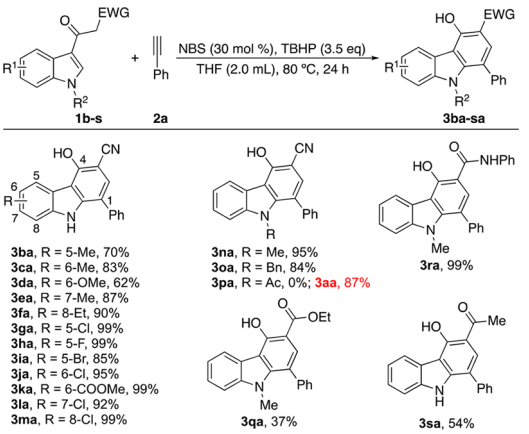


[a]Reaction conditions: **1a** (0.5 mmol), **2** (1.0 mmol), NBS (30 mol %), TBHP (3.5 equiv, 70% aqueous solution); isolated yield.

subsequently functionalized. When methyl acetylenecarboxylate **2v** and cyclopropylacetylene **2w** were subjected to the reaction conditions, the corresponding carbazole **3av** and **3aw** were obtained in 25% and 29% yields, respectively. An alkyne with a long alkyl chain could be similarly employed, albeit in a low yield (**3ax**, 12%).

The scope of the indoles was next examined using phenylacetylene **2a** as the starting material (Scheme 3). The electron-

Scheme 3. Variation of the indole component[a]



[a]Reaction conditions: **1** (0.5 mmol), **2a** (1.0 mmol), NBS (30 mol %), TBHP (3.5 equiv, 70% aqueous solution); isolated yield.

donating or -withdrawing character of the substituents on the indoles were well tolerated (**3ba**–**ma**), providing the products in moderate to excellent yields (62–99%). It should be mentioned that electron-donating groups somewhat retarded the annulation, and 6-OMe substrate **1d** gives only a 62% yield of **3da**. We were pleased to find that not only N–H indoles but also *N*-methyl and *N*-benzyl indoles reacted smoothly to yield the corresponding carbazoles in high yields (**3na** and **3oa**). Interestingly, the annulation of *N*-acetyl indole **1p** produced **3aa** rather than **3pa**. Obviously, the Ac group was released in this case. In addition to the cyano group, other electron-withdrawing groups in the side

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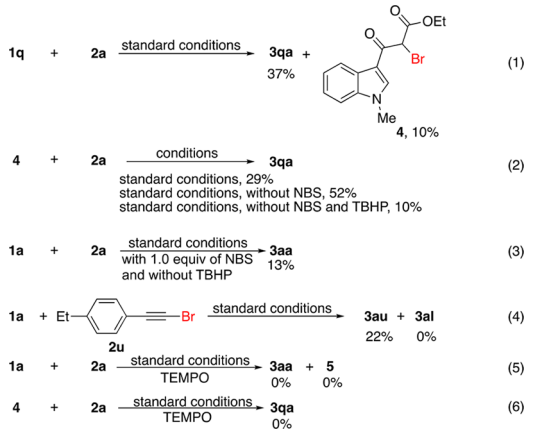
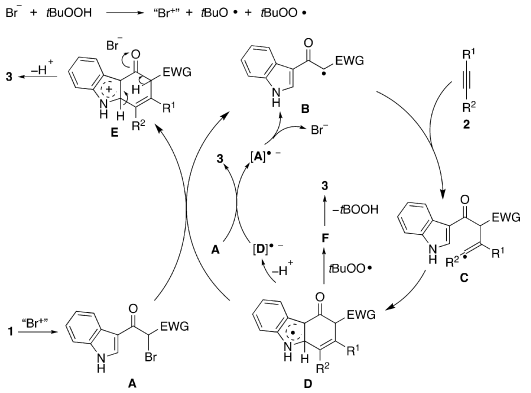
Scheme 4. Control Experiments



chain of acetyl indoles were also tested in the reaction (**3qa**−**sa**). The substrates with an ester, an amide, and a ketone converted to the desired carbazoles smoothly. Especially regarding **1r**, a quantitative yield was observed (**3ra**). When EWG was replaced with a phenyl, the annulation did not occur and the starting materials were recovered.

The mechanism of the annulation was investigated after we explored the substrate scope (Scheme 4). In the cycloaromatization reaction of **1q**, the bromination of **1q** occurred simultaneously, and the corresponding bromide **4** was isolated in 10% yield (eq 1). Independently prepared **4** was then subjected to reaction. Regardless if whether NBS was used or not, the reaction proceeded smoothly to yield the desired **3qa** (eq 2). Even in the absence of NBS and TBHP, **3qa** was obtained in 10% yield (eq 2). Moreover, 1.0 equiv of NBS could promote the reaction of **1a** with **2a** to give **3aa** in 13% yield in the absence of TBHP (eq 3). Similar control experiments were carried out with 1-(bromoethynyl)-4-ethylbenzene **2u**, which could be another possible intermediate generated by bromination of the alkyne. The carbazole bromide **3au** was isolated in 22% yield, and another potential product **3al** generated from the release of Br was not detected (eq 4). These results suggest that the α-bromination of acetyl indoles, rather than the bromination of alkynes, is involved in this cycloaromatization reaction. The free radical inhibition study was then carried out in the presence of TEMPO (3.5 equiv). The reaction was completely retarded by TEMPO, and neither **3aa** nor brominated intermediate **5** was detected (eq 5). We further performed a free radical inhibition study on the reaction of bromide **4** with **2a**. Product **3qa** was not detected either (eq 6). Obviously, TEMPO not only inhibited the whole reaction but also destroyed the annulation of the resulting intermediate **4** with alkyne **2a**. Based on the above results and previous reports,[11,23] a mechanistic pathway is proposed (Scheme 5). First, an oxidation of NBS occurs to produce active species "Br^{+}" (Br_2, BrOH, BrO^{-}, and $BrOH_2^{+}$),[24] as well as *t*BuO· and *t*BuOO· via the SET process. These "Br^{+}" species undergo bromination with **1** to give intermediate **A**.[21,25] The initiation reaction provides radical **B**, which is generated through hemolysis of the C−Br bond of intermediate **A** or through H-abstraction from **1**. Next, radical **B** enters an innate chain cycle[26] and couples with alkyne **2** yielding vinyl radical **C**,[11,23a,b] whose accessibility and stability determine the regioselectivity of annulation. That is, the stable arylvinyl radicals are formed preferentially in the cases of arylacetylenes, leading to carbazoles with complete regioselectivity. An intramolecular homolytic aromatic substitution (HAS) of **C** subsequently takes place to provide radical intermediate **D**.[11,23]

Scheme 5. Proposed Mechanism



Regeneration of the radical **B** is achieved through SET oxidation of **D** by bromide **A** to the corresponding cationic intermediate **E**, which upon deprotonation eventually provides carbazole **3** (outside cycle). The released Br^{-} is oxidized by *t*BuOOH to regenerate "Br^{+}". Alternatively, the radical **D** can first be deprotonated to a radical anion $[\mathbf{D}]^{\bullet-}$, which then reduces the bromide **A** to give radical anion $[\mathbf{A}]^{\bullet-}$, thereby forming the product **3**. Radical anion $[\mathbf{A}]^{\bullet-}$ subsequently fragments to radical **B** and Br^{-} (inside cycle).[26] In addition, it is also possible that the radical−radical coupling of **D** with more stabilized radical *t*BuOO· produces intermediate **F**, which forms carbazole **3** through ionic elimination of *t*BuOOH.[27]

In summary, we have developed an efficient and scalable method for the intermolecular annulation of acetyl indoles with alkynes through direct C−H bond functionalization. The carbazoles are smoothly formed under mild and metal-free conditions. The use of NBS as the catalyst allows the formation of C−C bonds from C_{sp^3}, C_{sp^2}, and C_{sp} bonds with complete regioselectivity. Further development and applications of this cycloaromatization in (hetero)aromatic rings synthesis are ongoing in our laboratory. We hope that the simple and commercially available bromine reagents will find new applications in organic synthesis, especially in green and sustainable chemistry.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.orglett.7b03021.

Detailed experimental procedures and spectral data (PDF)

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Notes

The authors declare no competing financial interest.

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REFERENCES

(1) (a) Knölker, H.-J.; Reddy, K. R. *Chem. Rev.* **2002**, *102*, 4303. (b) Issa, S.; Walchshofer, N.; Kassab, I.; Termoss, H.; Chamat, S.; Geahchan, A.; Bouaziz, Z. *Eur. J. Med. Chem.* **2010**, *45*, 2567. (c) Schmidt, A. W.; Reddy, K. R.; Knölker, H.-J. *Chem. Rev.* **2012**, *112*, 3193. (d) Maneerat, W.; Ritthiwigrom, T.; Cheenpracha, S.; Promgool, T.; Yossathera, K.; Deachathai, S.; Phakhodee, W.; Laphookhieo, S. *J. Nat. Prod.* **2012**, *75*, 741. (e) Zhang, J.; Du, Y.; Zhang, Q.; Lei, Y. *Talanta* **2014**, *119*, 193. (f) Diogo, L. N.; Pereira, S. A.; Nunes, A. R.; Afonso, R. A.; Santos, A. I.; Monteiro, E. C. *Eur. J. Pharmacol.* **2015**, *765*, 58.

(2) (a) Curiel, D.; Sanchez, G. Ramirez de Arellano, C.; Tarraga, A.; Molina. *Org. Biomol. Chem.* **2012**, *10*, 1896. (b) Kim, M.; Jeon, S. K.; Hwang, S.-H.; Lee, J. Y. *Synth. Met.* **2015**, *209*, 19. (c) Qureshi, M.; Chetia, T. R.; Ansari, M. S.; Soni, S. S. *J. Mater. Chem. A* **2015**, *3*, 4291.

(3) Robinson, B. *Chem. Rev.* **1969**, *69*, 227.

(4) Bucherer, H. T.; Seyde, F. *J. Prakt. Chem.* **1908**, *77*, 403.

(5) Cadogan, J. I. G.; Cameron-Wood, M.; Mackie, R. K.; Searle, R. J. G. *J. Chem. Soc.* **1965**, 4831.

(6) Graebe, C.; Ullmann, F. *Liebigs Ann. Chem.* **1896**, *291*, 16.

(7) (a) Wu, J.; Xie, Y. J.; Chen, X.; Deng, G. J. *Adv. Synth. Catal.* **2016**, *358*, 3206. (b) Liu, C.-Y.; Knochel, P. *Org. Lett.* **2005**, *7*, 2543. (c) Freeman, A. W.; Urvoy, M.; Criswell, M. E. *J. Org. Chem.* **2005**, *70*, 5014. (d) Liu, C.-Y.; Knochel, P. *J. Org. Chem.* **2007**, *72*, 7106. (e) Ackermann, L.; Althammer, A. *Angew. Chem., Int. Ed.* **2007**, *46*, 1627. (f) Kuethe, J. T.; Childers, K. G. *Adv. Synth. Catal.* **2008**, *350*, 1577. (g) Stokes, B. J.; Jovanović, B.; Dong, H.; Richert, K. J.; Riell, R. D.; Driver, T. G. *J. Org. Chem.* **2009**, *74*, 3225. (h) Alcaide, B.; Almendros, P.; Alonso, J. M.; Quirós, M. T.; Gadziński, P. *Adv. Synth. Catal.* **2011**, *353*, 1871. (i) Qiu, Y.; Kong, W.; Fu, C.; Ma, S. *Org. Lett.* **2012**, *14*, 6198. (j) Chakrabarty, S.; Chatterjee, I.; Tebben, L.; Studer, A. *Angew. Chem., Int. Ed.* **2013**, *52*, 2968. (k) Li, Q.; Peng, X.-S.; Wong, H. N. C. *Org. Chem. Front.* **2014**, *1*, 1197. (l) Poudel, T. N.; Lee, Y. R. *Chem. Sci.* **2015**, *6*, 7028. (m) Alcaide, B.; Almendros, P.; Alonso, J. M.; Busto, E.; Fernández, I.; Ruiz, M. P.; Xiaokaiti, G. *ACS Catal.* **2015**, *5*, 3417. (n) Wu, J.; Chen, X. G.; Xie, Y. J.; Guo, Y. J.; Zhang, Q.; Deng, G. J. *J. Org. Chem.* **2017**, *82*, 5743.

(8) (a) Yamashita, M.; Horiguchi, H.; Hirano, K.; Satoh, T.; Miura, M. *J. Org. Chem.* **2009**, *74*, 7481. (b) Tang, R.-Y.; Li, J.-H. *Chem. - Eur. J.* **2010**, *16*, 4733. (c) Verma, A. K.; Danodia, A. K.; Saunthwal, R. K.; Patel, M.; Choudhary, D. *Org. Lett.* **2015**, *17*, 3658. (d) Laha, J. K.; Dayal, N. *Org. Lett.* **2015**, *17*, 4742. (e) Saunthwal, R. K.; Patel, M.; Kumar, S.; Danodia, A. K.; Verma, A. K. *Chem. - Eur. J.* **2015**, *21*, 18601. (f) Bhunia, S. K.; Polley, A.; Natarajan, R.; Jana, R. *Chem. - Eur. J.* **2015**, *21*, 16786. (g) Lee, J. Y.; Ha, H.; Bae, S.; Han, I.; Joo, J. M. *Adv. Synth. Catal.* **2016**, *358*, 3458. (h) An, Y. L.; Yang, Z. H.; Zhang, H. H.; Zhao, S. Y. *Org. Lett.* **2016**, *18*, 152. (i) Ozaki, K.; Matsuoka, W.; Ito, H.; Itami, K. *Org. Lett.* **2017**, *19*, 1930.

(9) Pirovano, V.; Borri, M.; Abbiati, G.; Rizzato, S.; Rossi, E. *Adv. Synth. Catal.* **2017**, *359*, 1912.

(10) Krishna, N. H.; Saraswati, A. P.; Sathish, M.; Shankaraiah, N.; Kamal, A. *Chem. Commun.* **2016**, *52*, 4581.

(11) Yuan, Z. G.; Wang, Q.; Zheng, A.; Zhang, K.; Lu, L. Q.; Tang, Z.; Xiao, W. J. *Chem. Commun.* **2016**, *52*, 5128.

(12) Shi, L. J.; Zhong, X.; She, H. D.; Lei, Z. Q.; Li, F. W. *Chem. Commun.* **2015**, *51*, 7136.

(13) Zhu, C.; Ma, S. *Org. Lett.* **2014**, *16*, 1542.

(14) Ozaki, K.; Zhang, H.; Ito, H.; Lei, A.; Itami, K. *Chem. Sci.* **2013**, *4*, 3416.

(15) (a) Praveen, C.; Perumal, P. T. *Synlett* **2011**, *2011*, 521. (b) Rathore, K. S.; Harode, M.; Katukojvala, S. *Org. Biomol. Chem.* **2014**, *12*, 8641. (c) Wu, J. Q.; Yang, Z.; Zhang, S. S.; Jiang, C. Y.; Li, Q. J.; Huang, Z. S.; Wang, H. G. *ACS Catal.* **2015**, *5*, 6453. (d) Guo, T. L.; Jiang, Q. B.; Huang, F.; Chen, J. P.; Yu, Z. K. *Org. Chem. Front.* **2014**, *1*, 707. (e) Abid, M.; Spaeth, A.; Török, B. *Adv. Synth. Catal.* **2006**, *348*, 2191. (f) Zheng, X.; Lv, L.; Lu, S.; Wang, W.; Li, Z. *Org. Lett.* **2014**, *16*, 5156. (g) Wang, S. Y.; Chai, Z.; Wei, Y.; Zhu, X. C.; Zhou, S. L.; Wang, S. W. *Org. Lett.* **2014**, *16*, 3592. (h) Guney, T.; Lee, J. J.; Kraus, G. A. *Org. Lett.* **2014**, *16*, 1124. (i) Zhao, J. J.; Li, P.; Xia, C. G.; Li, F. W. *Chem. - Eur. J.* **2015**, *21*, 16383. (j) Biswas, S.; Dagar, A.; Srivastava, A.; Samanta, S. *Eur. J. Org. Chem.* **2015**, *2015*, 4493. (k) Chen, S. P.; Li, Y. X.; Ni, P. H.; Huang, H. W.; Deng, G. J. *Org. Lett.* **2016**, *18*, 5384. (l) Huang, Y. W.; Li, X. Y.; Fu, L. N.; Guo, Q. X. *Org. Lett.* **2016**, *18*, 6200. (m) Reddy, C. R.; Valleti, R. R.; Dilipkumar, U. *Chem. - Eur. J.* **2016**, *22*, 2501. (n) Banerjee, A.; Sahu, S.; Maji, M. S. *Adv. Synth. Catal.* **2017**, *359*, 1860. (o) Chen, S. P.; Li, Y. X.; Ni, P. H.; Yang, B. C.; Huang, H. W.; Deng, G. J. *J. Org. Chem.* **2017**, *82*, 2935. (p) Biswas, S.; Majee, D.; Dagar, A.; Samanta, S. *Synlett* **2014**, *25*, 2115.

(16) (a) Yeung, C. S.; Dong, V. M. *Chem. Rev.* **2011**, *111*, 1215. (b) Girard, S. A.; Knauber, T.; Li, C.-J. *Angew. Chem., Int. Ed.* **2014**, *53*, 74.

(17) (a) Uyanik, M.; Ishihara, K. *ChemCatChem* **2012**, *4*, 177. (b) Finkbeiner, P.; Nachtsheim, B. J. *Synthesis* **2013**, *45*, 979. (c) Wu, X. F.; Gong, J. L.; Qi, X. X. *Org. Biomol. Chem.* **2014**, *12*, 5807. (d) Liu, D.; Lei, A. *Chem. - Asian J.* **2015**, *10*, 806.

(18) Saikia, I.; Borah, A. J.; Phukan, P. *Chem. Rev.* **2016**, *116*, 6837.

(19) (a) Talluri, S. K.; Sudalai, A. *Org. Lett.* **2005**, *7*, 855. (b) Shaterian, H. R.; Yarahmadi, H.; Ghashang, M.; Safari Mehmandosti, M. *Chin. J. Chem.* **2008**, *26*, 2093. (c) Habibzadeh, S.; Ghasemnejad, H.; Faraji, M. *Helv. Chim. Acta* **2011**, *94*, 429. (d) Zhou, L.; Chen, J.; Zhou, J.; Yeung, Y.-Y. *Org. Lett.* **2011**, *13*, 5804. (e) Ghorbani-Vaghei, R.; Malaekehpoor, S. M. *Tetrahedron Lett.* **2012**, *53*, 4751. (f) Guo, F.; Wang, L.; Mao, S.; Zhang, C.; Yu, J.; Han, J. *Tetrahedron* **2012**, *68*, 8367. (g) Gong, L.; Xing, L.-J.; Xu, T.; Zhu, X.-P.; Zhou, W.; Kang, N.; Wang, B. *Org. Biomol. Chem.* **2014**, *12*, 6557. (h) Liang, Y.-F.; Wu, K.; Song, S.; Li, X.; Huang, X.; Jiao, N. *Org. Lett.* **2015**, *17*, 876.

(20) (a) Madabhushi, S.; Jillella, R.; Mallu, K. K. R.; Godala, K. R.; Vangipuram, V. S. *Tetrahedron Lett.* **2013**, *54*, 3993. (b) Wang, J.-Y.; Jiang, Q.; Guo, C.-C. *Synth. Commun.* **2014**, *44*, 3130. (c) Dighe, S. U.; Batra, S. *Adv. Synth. Catal.* **2016**, *358*, 500. (d) Sriramoju, V.; Jillella, R.; Kurva, S.; Madabhushi, S. *Chem. Lett.* **2017**, *46*, 560. (e) Wu, C.; Xin, X.; Fu, Z. M.; Xie, L. Y.; Liu, K. J.; Wang, Z.; Li, W. Y.; Yuan, Z. H.; He, W. M. *Green Chem.* **2017**, *19*, 1983.

(21) Podgoršek, A.; Zupan, M.; Iskra, J. *Angew. Chem., Int. Ed.* **2009**, *48*, 8424.

(22) CCDC 1441579.

(23) (a) Hartmann, M.; Daniliuc, C. G.; Studer, A. *Chem. Commun.* **2015**, *51*, 3121. (b) Jiang, H.; Cheng, Y.; Zhang, Y.; Yu, S. *Org. Lett.* **2013**, *15*, 4884. (c) Chen, Z.-Z.; Liu, S.; Hao, W.-J.; Xu, G.; Wu, S.; Miao, J.-N.; Jiang, B.; Wang, S.-L.; Tu, S.-J.; Li, G. *Chem. Sci.* **2015**, *6*, 6654.

(24) (a) Bray, W. C. *Chem. Rev.* **1932**, *10*, 161. (b) Detty, M. R.; Zhou, F.; Friedman, A. E. *J. Am. Chem. Soc.* **1996**, *118*, 313. (c) Drake, M. D.; Bateman, M. A.; Detty, M. R. *Organometallics* **2003**, *22*, 4158. (d) Podgorsek, A.; Stavber, S.; Zupan, M.; Iskra, J. *Green Chem.* **2007**, *9*, 1212.

(25) (a) Barhate, N. B.; Gajare, A. S.; Wakharkar, R. D.; Bedekar, A. V. *Tetrahedron* **1999**, *55*, 11127. (b) Espenson, J. H.; Zhu, Z.; Zauche, T. H. *J. Org. Chem.* **1999**, *64*, 1191.

(26) (a) Arceo, E.; Montroni, E.; Melchiorre, P. *Angew. Chem., Int. Ed.* **2014**, *53*, 12064. (b) Studer, A.; Curran, D. P. *Angew. Chem., Int. Ed.* **2016**, *55*, 58. (c) Studer, A.; Curran, D. P. *Nat. Chem.* **2014**, *6*, 765.

(27) Studer, A. *Chem. - Eur. J.* **2001**, *7*, 1159.

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