Organic LETTERS

Letter

Cite This: Org. Lett. XXXX, XXX, XXX−XXX

pubs.acs.org/OrgLett

# Alkylamination of Styrenes with Alkyl *N*-Hydroxyphthalimide Esters and Amines by $B(C_6H_5)_3$-Facilitated Photoredox Catalysis

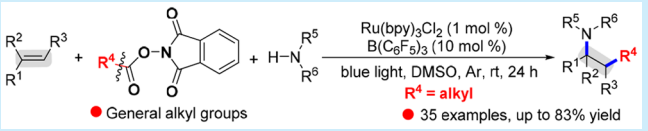
Xuan-Hui Ouyang,[†] Yang Li,[†] Ren-Jie Song,*[,†] and Jin-Heng Li*[,†,‡]

[†]Key Laboratory of Jiangxi Province for Persistent Pollutants Control and Resources Recycle, Nanchang Hangkong University, Nanchang 330063, China

[‡]State Key Laboratory of Applied Organic Chemistry, Lanzhou University, Lanzhou 730000, China

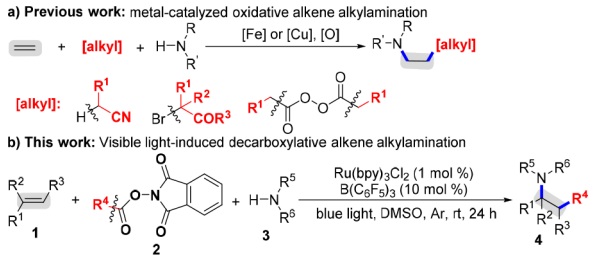
Supporting Information

**ABSTRACT:** A new, three-component 1,2-alkylamination of styrenes with alkyl *N*-hydroxyphthalimide (NHP) esters and amines by Lewis acid and visible-light photoredox cooperative catalysis is described. This reaction employs alkyl NHP esters as general alkylation reagents to accomplish the 1,2-alkylamination of alkenes in high efficiency and with excellent functional groups tolerance, significantly enhancing the synthetic potential of 1,2-alkylaminations of alkenes for accessing complex functionalized amines.




Amines are an important class of common compounds that possess unique bioactivities and chemical properties and, thus, serve not only as a key structural motif in numerous natural products and pharmaceuticals but also as important synthetic building blocks in synthesis. Among the efficient methods that have been established for constructing diversely functionalized amines,[1] the carboamination of alkenes has proven to be a particularly powerful technology for incorporating amine elements across C=C bonds leading to valuable amino-functionalized molecules.[2,3] However, examples of the alkylamination of alkenes in which an amine and an alkyl group are simultaneously introduced across the C=C bond of an alkene are rare (Scheme 1a).[3] Recently, we reported a new 1,2-alkylamination of alkenes to access γ-amino alkyl nitriles by using alkyl nitriles as the alkyl sources in the presence of an amines, and the reaction is catalyzed by Lewis acidic iron and $Ag_2CO_3$ is used as the oxidant.[3a] Bao and co-workers[3b] have employed aliphatic diacyl peroxides as general alkylating and oxidizing agents and nitriles as nitrogen sources to extend an Fe-catalyzed alkene alkylamination methodology. The Hull group[3c] and our group[3d,e] independently developed a Cu-catalyzed oxidative intermolecular 1,2-alkylamination of alkenes with alkyl bromides and amines for the synthesis of γ-amino esters and pyrrolidin-2-ones; however, the reactions are limited to α-bromoalkyl esters. Thus, new and efficient strategies for intermolecular alkene 1,2-alkylamination, especially including utilizations of new alkylation reagents, are still highly appealing.

**Scheme 1. Intermolecular Alkene 1,2-Alkylamination**




Alkyl NHP esters have become general and readily available alkylation reagents for decarboxylation reactions under visible-light photoredox catalysis or metal catalysis.[4−7] However, the vast majority of successful approaches focus on two-component decarboxylative alkylation processes, most likely due to the high instability of the alkyl radicals. Typical approaches include transformations of alkyl NHP esters with alkenes, and most of these reactions are limited to a two-component decarboxylative Heck-type alkylation reaction and hydroalkylation process.[5] In 2017, the Glorius group[6a] reported a new multicomponent oxyalkylation of styrenes with alkyl NHP esters and $H_2O$ or alcohols, which was achieved by activating *N*-(acyloxy)phthalimides toward photoinduced electron transfer through hydrogen bonding. Subsequently, the Glorius group[6b] and the Ye group[6c] independently employed DMSO as the oxygen source and oxidant to realize the oxoalkylation of styrenes with alkyl NHP esters under photocatalysis. Very recently, a photoredox and copper-catalyzed asymmetric cyanoalkylation using alkyl NHP esters as alkylation reagents and TMSCN as the CN source was developed.[6g] On the basis of these results, we envisioned that the combination of a Lewis acid and a photocatalyst might allow the reactivity of the alkyl radicals to be controlled, providing selective for addition across the C=C bond and suppressing the competitive direct coupling with strong nucleophiles and β-H elimination. Herein, we report a novel three-component 1,2-alkylamination of alkenes with alkyl NHP

**Received:** August 21, 2018







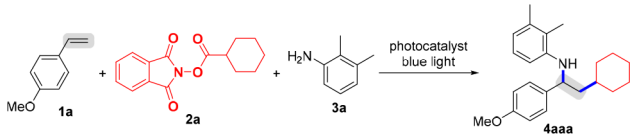


DOI: 10.1021/acs.orglett.8b02670
Org. Lett. XXXX, XXX, XXX−XXX

esters and amines enabled by the synergistic combination of photoredox and Lewis acid catalysts to produce valuable alkyl-functionalized amines (Scheme 1b). Employing the combination of $Ru(bpy)_3Cl_2$, $B(C_6H_5)_3$, and blue light allows the formation of two new chemical bonds, namely, a $C(sp^3)$–$C(sp^3)$ bond and a $C(sp^3)$–N bond, in good efficiency through a decarboxylative generation of an alkyl radicals, addition across the alkenes, and nucleophilic amination cascade process.

Our study of the 1,2-aminoalkylation of alkenes began with exposure of the three reaction partners, 4-methoxystyrene **1a**, cyclohexyl NHP ester **2a**, and 2,3-dimethylaniline, to the visible-light cooperative catalysis system (Table 1). Employing

**Table 1. Screening of Optimal Reaction Conditions**[a]



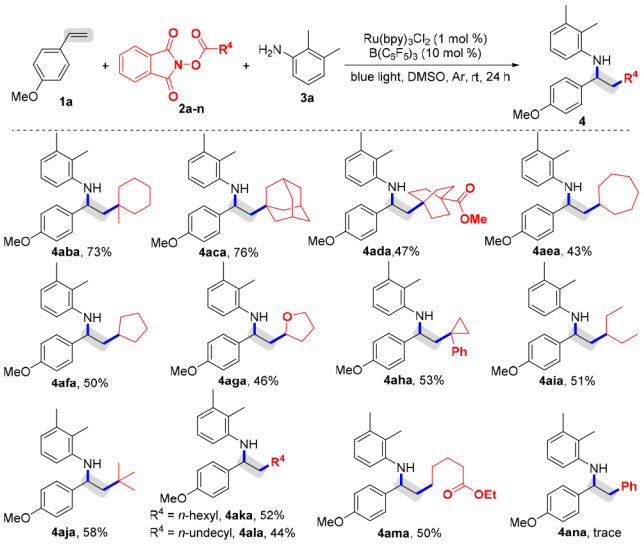

| entry | photocatalyst | additive | solvent | yield (%) |
|---|---|---|---|---|
| 1 | $Ir(ppy)_3$ | | DMSO | 31 |
| 2 | $Ir(ppy)_3$ | | NMP | 7 |
| 3 | $Ir(ppy)_3$ | | MeCN | 9 |
| 4 | $[Ir(dtbbpy)(ppy)_2](PF_6)_2$ | | DMSO | 34 |
| 5 | $Ru(bpy)_3Cl_2$ | | DMSO | 38 |
| 6 | Eosin Y | | DMSO | 5 |
| 7[b] | $Ru(bpy)_3Cl_2$ | | DMSO | 24 |
| 8 | $Ru(bpy)_3Cl_2$ | $BF_3{\cdot}Et_2O$ | DMSO | 36 |
| 9 | $Ru(bpy)_3Cl_2$ | $Fe(OTf)_3$ | DMSO | 32 |
| 10 | $Ru(bpy)_3Cl_2$ | $NiBr_2$ | DMSO | 31 |
| 11 | $Ru(bpy)_3Cl_2$ | $B(C_6F_5)_3$ | DMSO | 52 |
| 12[c] | $Ru(bpy)_3Cl_2$ | $B(C_6F_5)_3$ | DMSO | 50 |

[a]Reaction conditions: **1a** (0.2 mmol), **2a** (1.5 equiv), **3a** (1.5 equiv), photocatalyst (1 mol %), additive (10 mol %), solvent (1 mL), 5 W LED blue light, argon, room temperature, and 24 h. Some byproducts, including (*E*)-1-(2-cyclohexylvinyl)-4- methoxybenzene **5aa** and *N*-cyclohexyl-2,3-dimethylaniline **6aa**, were observed as determined by GC–MS analysis. [b]36 W compact fluorescent light. [c]At 40 °C.

$Ir(ppy)_3$ photocatalyst and blue light in DMSO, the desired product **4aaa** was formed in 31% yield (entry 1). Two other solvents, 1-methyl-pyrrolidin-2-one (NMP; entry 2) and MeCN (entry 3), showed lower reactivity than DMSO. A survey of photocatalysts proved $Ru(bpy)_3Cl_2$ to be the optimal choice, as the other three photocatalysts (entries 4–6), namely, $Ir(ppy)_3$, $[Ir(dtbbpy)(ppy)_2](PF_6)_2$, and eosin Y, all gave lower yields than $Ru(bpy)_3Cl_2$. A compact fluorescent light also accommodated the reaction, albeit in diminished yield (entry 7). Gratifyingly, Lewis acids, such as $BF_3{\cdot}Et_2O$, $Fe(OTf)_3$, $NiBr_2$, and $B(C_6F_5)_3$, were found to affect the reaction (entries 8–11). While the first three Lewis acids had a deleterious effect (entries 8–10), the last $B(C_6F_5)_3$ Lewis acids enhanced the yield of **4aaa** to 52% yield (entry 11). A higher temperature (40 °C) was screened with no improvement on the yield (entry 12).

With the optimal reaction conditions in hand, we explored the scope of this three-component 1,2-aminoalkylation protocol with respect to alkyl NHP esters **2b–n** (Scheme 2). In the presence of alkene **1a** and amine **3a**, $Ru(bpy)_3Cl_2$, $B(C_6F_5)_3$, and blue light, a variety of alkyl NHP esters **2b–m** comprising 1°, 2°, and 3° alkyl groups were all suitable

**Scheme 2. Variations of the Alkyl NHP Esters (2)**[a]




[a]Reaction conditions: **1a** (0.2 mmol), **2** (1.5 equiv), **3a** (1.5 equiv), $Ru(bpy)_3Cl_2$ (1 mol %), $B(C_6F_5)_3$ (10 mol %), DMSO (1 mL), 5 W LED blue light, argon, room temperature, and 24 h.

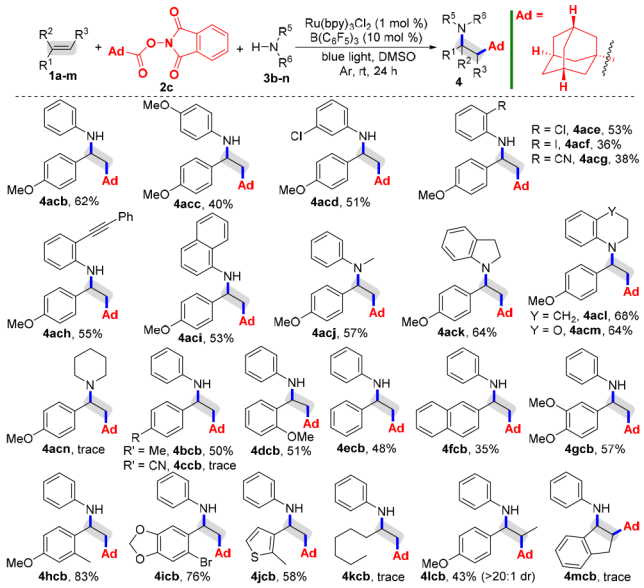
substrates and provided **4aba–ama** in moderate to good yields, and 3° alkyl groups were more reactive than 1° and 2° alkyl groups. 1-Methylcyclohexyl- or adamantyl-possessing NHP esters **2b,c** and **4aba–aca** were delivered in high yields, but 3° bridge ring-containing NHP ester **2d** furnished **4ada** in moderate yield, probably due to the electron-withdrawing ester group. The 2° alkyl groups, including cycloheptyl (**2e**), cyclopentyl (**2f**), tetrahydrofuran-2-yl (**2g**), and pent-3-yl (**2i**), led to **4aea–aga** and **4aia** in moderate yields. Two other 3° alkyl groups, 1-phenylcyclopropyl (**2h**) and *tert*-butyl (**2j**), were well accommodated to assemble **4aha** and **4aja**. Using 1° alkyl groups, such as *n*-hexyl (**2k**), *n*-undecyl (**2l**), and 4-ethoxy-4-oxobutyl (**2m**), enabled the formation of **4aka–ama**. For example, 4-ethoxy-4-oxobutyl NHP ester **2m** was smoothly transformed into **4ama**, showing that an ester group was tolerated. Unfortunately, phenyl NHP ester **2n** was unsuitable for the reaction (**4ana**).

This three-component 1,2-aminoalkylation protocol was general for styrenes **1a–m** and amines **3b–n** (Scheme 3). In the presence of adamantyl NHP ester **2c**, $Ru(bpy)_3Cl_2$, and $B(C_6F_5)_3$ under blue light, a variety of other primary arylamines **3b–i** were suitable substrates for accessing **4acb–aci** in moderate yields, and a number of substituents, including MeO, Cl, I, CN, and phenylethynyl, on the aryl ring were tolerated. Both aniline **3b** and naphthalen-1-amine **3i** were successfully introduced across the alkene **1a** (**4acb** and **4aci**). Using valuable secondary amines, such as *N*-methylaniline **3j**, indoline **3k**, 1,2,3,4-tetrahydroquinoline **3l**, and 3,4-dihydro-2*H*-benzo-[*b*][1,4]oxazine **3m**, efficiently enabled the formation of the desired products **4acj–acm**. However, piperidine, an aliphatic amine, had no reactivity (**4acn**). We found that the optimal conditions were compatible with a wide range of terminal arylalkenes **1b**, **1d–j** (**4bcb**, **4dcb–jcb**) and an internal alkene **1l** (**4lcb**) but did not work with the electron-deficient *p*-CN-substituted arylalkene **1c** (**4ccb**), alkylalkene **1k** (**4kcb**), and indene **1m** (**4mcb**). In the case of styrenes **1b** and **1d** comprising a *p*-Me or an *o*-MeO group, the reaction proceeded smoothly to furnish **4bcb** and **4dcb** in moderate



DOI: 10.1021/acs.orglett.8b02670
*Org. Lett.* XXXX, XXX, XXX–XXX

**Scheme 3. Variations of the Alkenes (1) and Amines (3)**[a]

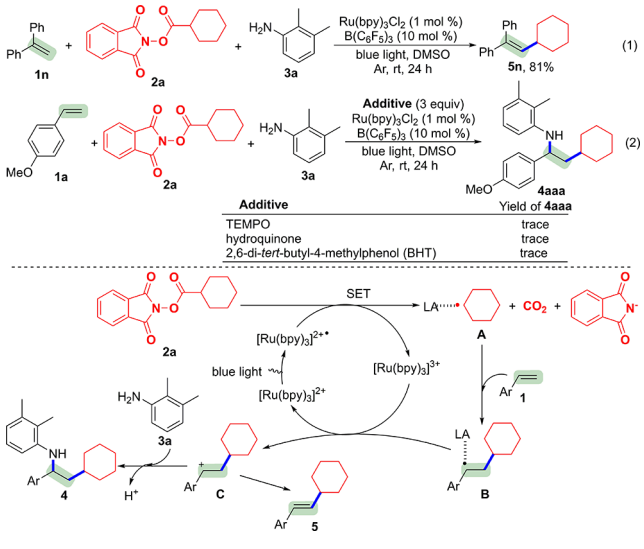



[a]Reaction conditions: **1** (0.2 mmol), **2c** (1.5 equiv), **3** (1.5 equiv), $Ru(bpy)_3Cl_2$ (1 mol %), $B(C_6F_5)_3$ (10 mol %), DMSO (1 mL), 5 W LED blue light, argon, room temperature, and 24 h.

yields. Both styrene **1e** and 1-vinylnaphthalene **1f** were suitable substrates, but the yields of the corresponding products (**4ecb**–**fcb**) were lower. Disubstituted styrenes **1h,i** were found to be highly reactive, giving **4hcb**–**icb** in high yields. It was noted that 2-methyl-3-vinylthiophene **1j** provided sulfur-containing heteroaryl-functionalized product **4jcb**. This protocol was applicable to internal alkene **1l**, which gave **4lcb** in 43% yield. However, it could not run with indene **1l** (**4lcb**). Surprisingly, 1,1-diphenylethene **1n** only afforded the Heck-type product **5n** (eq 1; Scheme 4).

To gain insight into the mechanism, control experiments of alkene **1a** with NHP ester **2a** and amine **3a** were conducted in the presence of a radical inhibitor, such as TEMPO, hydroquinone, and BHT (eq 2; Scheme 4). The reaction was completely suppressed, which supports a radical process.

**Scheme 4. Control Experiments and Possible Mechanism**




The plausible mechanism for this three-component alkene 1,2-aminoalkylation protocol is outlined in Scheme 4.[2−5,7] With the aid of visible-light photoredox catalysis and $B(C_6F_5)_3$, cyclohexyl NHP ester **2a** is decomposed and generates the cyclohexyl radical **A**, $CO_2$, and phthalimide anion. Addition of the cyclohexyl radical **A** across the C=C bond of arylalkene **1** selectively occurs to form alkyl radical **B**, which sequentially undergoes single electron oxidation by the $[Ru(bpy)_3]^{3+}$ species to afford the alkyl cation intermediate **C**. Finally, the reaction of the intermediate **C** with nucleophilic amine **3a** delivers the desired product **4**. Meanwhile, intermediate **C** resulted in the formation of byproduct **5** via $\beta$-H elimination. The quantum yield ($\Phi x$ = 0.014) rules out a chain mechanism.[8]

During the processes, both intermediates **B** and **C** require conjugation of the Lewis acid to make them sufficiently stable; thus, only styrenes display high reactivity. $B(C_6F_5)_3$ might serve as a Lewis acid to activate the *N*-(acyloxy)phthalimides, intermediate **A**, and intermediate **B**.

In summary, we have developed a novel, three-component 1,2-aminoalkylation of styrenes by Lewis acid and visible-light photoredox cooperative catalysis in which alkyl *N*-hydroxyphthalimide esters are employed as the alkylation reagents and are used amines as the nucleophilic termination reagents. This reaction provides a practical route to access various functionalized secondary and tertiary amines through the formation of two new chemical bonds, a $C(sp^3)$–$C(sp^3)$ bond and a $C(sp^3)$–N bond. Moreover, the reaction features high selectivity and broad substrate scope with regard to a wide range of styrenes, alkylation reagents, and amines; thus, this reaction represents an indisputable advance in the 1,2-aminoalkylation of alkene field for the construction of valuable amine architectures.

## ■ ASSOCIATED CONTENT

### Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.orglett.8b02670.

Descriptions of experimental procedures for compounds, and analytical characterization (PDF)

## ■ AUTHOR INFORMATION


### Corresponding Authors

*E-mail: srj0731@hnu.edu.cn.
*E-mail: jhli@hnu.edu.cn.

### ORCID

Ren-Jie Song: 0000-0001-8708-7433
Jin-Heng Li: 0000-0001-7215-7152


### Notes

The authors declare no competing financial interest.

## ■ ACKNOWLEDGMENTS

We thank the National Natural Science Foundation of China (Nos. 21625203 and 21472039) and the Jiangxi Province Science and Technology Project (Nos. 20171ACB20015 and 20165BCB18007) for financial support.



DOI: 10.1021/acs.orglett.8b02670
*Org. Lett.* XXXX, XXX, XXX−XXX

## REFERENCES


(1) For selected recent reviews, see: (a) Wills, M. *Top. Curr. Chem.* **2016**, *374*, 14. (b) Chauhan, P.; Mahajan, S.; Enders, D. *Acc. Chem. Res.* **2017**, *50*, 2809. (c) Glennon, R. A. *J. Med. Chem.* **2017**, *60*, 2605. (d) Meanwell, N. A. *J. Med. Chem.* **2018**, *61*, 5822. (e) Chemler, S. R.; Karyakarte, S. D.; Khoder, Z. M. *J. Org. Chem.* **2017**, *82*, 11311. (f) Huang, D.; Yan, G. *Adv. Synth. Catal.* **2017**, *359*, 1600. (g) Ruiz-Castillo, P.; Buchwald, S. L. *Chem. Rev.* **2016**, *116*, 12564. (h) Lauder, K.; Toscani, A.; Scalacci, N.; Castagnolo, D. *Chem. Rev.* **2017**, *117*, 14091. (i) Zhang, R.; Luo, S. *Chin. Chem. Lett.* **2018**, *29*, 1193.

(2) (a) Surhone, L. M.; Tennoe, M. T.; Henssonow, S. F. *Vicinal Difunctionalization*; Betascript Publishing, 2010. (b) Chemler, S. R.; Fuller, P. H. *Chem. Soc. Rev.* **2007**, *36*, 1153. (c) Schultz, D. M.; Wolfe, J. P. *Synthesis* **2012**, *44*, 351. (d) Wolfe, J. P. *Angew. Chem., Int. Ed.* **2012**, *51*, 10224. (e) Xu, J.; Song, Q. *Youji Huaxue* **2016**, *36*, 1151. (f) Yin, G.; Mu, X.; Liu, G. *Acc. Chem. Res.* **2016**, *49*, 2413. (g) Ouyang, X.-H.; Song, R.-J.; Li, J.-H. *Chem. - Asian J.* **2018**, *13*, 2316. (h) Lin, J.; Song, R.-J.; Hu, M.; Li, J.-H. *Chem. Rec.* **2018**, DOI: 10.1002/tcr.201800053. (i) Giri, R.; KC, S. *J. Org. Chem.* **2018**, *83*, 3013.

(3) (a) Liu, Y.-Y.; Yang, X.-H.; Song, R.-J.; Luo, S.; Li, J.-H. *Nat. Commun.* **2017**, *8*, 14720. (b) Qian, B.; Chen, S.; Wang, T.; Zhang, X.; Bao, H. *J. Am. Chem. Soc.* **2017**, *139*, 13076. (c) Gockel, S. N.; Buchanan, T. L.; Hull, K. L. *J. Am. Chem. Soc.* **2018**, *140*, 58. (d) Pan, G.-H.; Ouyang, X.-H.; Hu, M.; Xie, Y.-X.; Li, J.-H. *Adv. Synth. Catal.* **2017**, *359*, 2564. (e) Pan, G.-H.; Song, R.-J.; Xie, Y.-X.; Luo, S.; Li, J.-H. *Synthesis* **2018**, *50*, 1651.

(4) (a) Barton, D. H. R.; Crich, D.; Motherwell, W. B. *J. Chem. Soc., Chem. Commun.* **1983**, 939. (b) Barton, D. H. R.; Crich, D.; Motherwell, W. B. *Tetrahedron Lett.* **1983**, *24*, 4979. (c) Saraiva, M. F.; Couri, M. R. C.; Le Hyaric, M.; deAlmeida, M. V. *Tetrahedron* **2009**, *65*, 3563. (d) Xuan, J.; Zhang, Z.-G.; Xiao, W.-J. *Angew. Chem., Int. Ed.* **2015**, *54*, 15632. (e) Huang, H.; Jia, K.; Chen, Y. *ACS Catal.* **2016**, *6*, 4983. (f) Shaw, M. H.; Twilton, J.; MacMillan, D. W. C. *J. Org. Chem.* **2016**, *81*, 6898. (g) Zard, S. Z. *Org. Lett.* **2017**, *19*, 1257. (h) Murarka, S. *Adv. Synth. Catal.* **2018**, *360*, 1735.

(5) (a) Okada, K.; Okamoto, K.; Morita, N.; Okubo, K.; Oda, M. *J. Am. Chem. Soc.* **1991**, *113*, 9401. (b) Schnermann, M. J.; Overman, L. E. *Angew. Chem., Int. Ed.* **2012**, *51*, 9576. (c) Pratsch, G.; Lackner, G. L.; Overman, L. E. *J. Org. Chem.* **2015**, *80*, 6025. (d) Slutskyy, Y.; Overman, L. E. *Org. Lett.* **2016**, *18*, 2564. (e) Jin, Y.; Yang, H.; Fu, H. *Org. Lett.* **2016**, *18*, 6400. (f) Xu, K.; Tan, Z.; Zhang, H.; Liu, J.; Zhang, S.; Wang, Z. *Chem. Commun.* **2017**, *53*, 10719. (g) Edwards, J. T.; Merchant, R. R.; McClymont, K. S.; Knouse, K. W.; Qin, T.; Malins, L. R.; Vokits, B.; Shaw, S. A.; Bao, D.; Wei, F.; Zhou, T.; Eastgate, M. D.; Baran, P. S. *Nature* **2017**, *545*, 213. (h) Wang, G.-Z.; Shang, R.; Fu, Y. *Org. Lett.* **2018**, *20*, 888. (i) Koy, M.; Sandfort, F.; Tlahuext-Aca, A.; Quach, L.; Daniliuc, C. G.; Glorius, F. *Chem. - Eur. J.* **2018**, *24*, 4552. (j) Zhao, Y.; Chen, J.-R.; Xiao, W.-J. *Org. Lett.* **2018**, *20*, 224. (k) Yang, J.-C.; Zhang, J.-Y.; Zhang, J.-J.; Duan, X.-H.; Guo, L.-N. *J. Org. Chem.* **2018**, *83*, 1598.

(6) Three-component oxyalkylation of styrenes using $H_2O$, alcohols, or DMSO as the oxygen source: (a) Tlahuext-Aca, A.; Garza-Sanchez, R. A.; Glorius, F. *Angew. Chem., Int. Ed.* **2017**, *56*, 3708. (b) Tlahuext-Aca, A.; Garza-Sanchez, R. A.; Schäfer, M.; Glorius, F. *Org. Lett.* **2018**, *20*, 1546. (c) Xia, Z.-H.; Zhang, C.-L.; Gao, Z.-H.; Ye, S. *Org. Lett.* **2018**, *20*, 3496. Three-component cyanoalkylation of styrenes using TMSCN as the CN resource: (d) Sha, W.; Deng, L.; Ni, S.; Mei, H.; Han, J.; Pan, Y. *ACS Catal.* **2018**, *8*, 7489. Two-component alkyllactonization of unsaturated carboxylic acids: (e) Sha, W.; Ni, S.; Han, J.; Pan, Y. *Org. Lett.* **2017**, *19*, 5900. Although two-component carboamination of alkenes has been established, *O*-vinylhydroxylamine derivatives serve as both the C (alkyl) and N (amido) donors to make this reaction still meet the aforementioned challenges: (f) Zhang, Y.; Liu, H.; Tang, L.; Tang, H.-J.; Wang, L.; Zhu, C.; Feng, C. *J. Am. Chem. Soc.* **2018**, *140*, 10695. (g) Asymmetric cyanoalkylation with alkyl *N*-hydroxyphthalimide esters: Wang, D.; Zhu, N.; Chen, P.; Lin, Z.; Liu, G. *J. Am. Chem. Soc.* **2017**, *139*, 15632.

(7) For selected pioneering and recent papers on other transformations of alkyl *N*-hydroxyphthalimide esters: (a) Lackner, G. L.; Quasdorf, K. W.; Overman, L. E. *J. Am. Chem. Soc.* **2013**, *135*, 15342. (b) Kachkovskyi, G.; Faderl, C.; Reiser, O. *Adv. Synth. Catal.* **2013**, *355*, 2240. (c) Yang, J.; Zhang, J.; Qi, L.; Hu, C.; Chen, Y. *Chem. Commun.* **2015**, *51*, 5275. (d) Jin, Y.; Yang, H.; Fu, H. *Chem. Commun.* **2016**, *52*, 12909. (e) Cornella, J.; Edwards, J. T.; Qin, T.; Kawamura, S.; Wang, J.; Pan, C.-M.; Gianatassio, R.; Schmidt, M.; Eastgate, M. D.; Baran, P. S. *J. Am. Chem. Soc.* **2016**, *138*, 2174. (f) Huihui, K. M. M.; Caputo, J. A.; Melchor, Z.; Olivares, A. M.; Spiewak, A. M.; Johnson, K. A.; DiBenedetto, T. A.; Kim, S.; Ackerman, L. K. G.; Weix, D. J. *J. Am. Chem. Soc.* **2016**, *138*, 5016. (g) Toriyama, F.; Cornella, J.; Wimmer, L.; Chen, T.; Dixon, D. D.; Creech, G.; Baran, P. S. *J. Am. Chem. Soc.* **2016**, *138*, 11132. (h) Wang, J.; Qin, T.; Chen, T.; Wimmer, L.; Edwards, J. T.; Cornella, J.; Vokits, B.; Shaw, S. A.; Baran, P. S. *Angew. Chem., Int. Ed.* **2016**, *55*, 9676. (i) Qin, T.; Cornella, J.; Li, C.; Malins, L. R.; Edwards, J. T.; Kawamura, S.; Maxwell, B. D.; Eastgate, M. D.; Baran, P. S. *Science* **2016**, *352*, 801. (j) Cheng, W.-M.; Shang, R.; Fu, M.-C.; Fu, Y. *Chem. - Eur. J.* **2017**, *23*, 2537. (k) Zhang, H.; Zhang, P.; Jiang, M.; Yang, H.; Fu, H. *Org. Lett.* **2017**, *19*, 1016. (l) Fawcett, A.; Pradeilles, J.; Wang, Y.; Mutsuga, T.; Myers, E. L.; Aggarwal, V. K. *Science* **2017**, *357*, 283. (m) Hu, D.; Wang, L.; Li, P. *Org. Lett.* **2017**, *19*, 2770. (n) Cheng, W.-M.; Shang, R.; Zhao, B.; Xing, W.-L.; Fu, Y. *Org. Lett.* **2017**, *19*, 4291. (o) Suzuki, N.; Hofstra, J. L.; Poremba, K. E.; Reisman, S. E. *Org. Lett.* **2017**, *19*, 2150. (p) Cheng, W.-M.; Shang, R.; Fu, Y. *ACS Catal.* **2017**, *7*, 907. (q) Zhang, J.-J.; Yang, J.-C.; Guo, L.-N.; Duan, X.-H. *Chem. - Eur. J.* **2017**, *23*, 10259. (r) Xue, W.; Oestreich, M. *Angew. Chem., Int. Ed.* **2017**, *56*, 11649. (s) Smith, J. M.; Qin, T.; Merchant, R. R.; Edwards, J. T.; Malins, L. R.; Liu, Z.; Che, G.; Shen, Z.; Shaw, S. A.; Eastgate, M. D.; Baran, P. S. *Angew. Chem., Int. Ed.* **2017**, *56*, 11906. (t) Wang, D.; Zhu, N.; Chen, P.; Lin, Z.; Liu, G. *J. Am. Chem. Soc.* **2017**, *139*, 15632. (u) Zhao, W.; Wurz, R. P.; Peters, J. C.; Fu, G. C. *J. Am. Chem. Soc.* **2017**, *139*, 12153. (v) Li, H.; Breen, C. P.; Seo, H.; Jamison, T. F.; Fang, Y.-Q.; Bio, M. M. *Org. Lett.* **2018**, *20*, 1338. (w) Ren, L.; Cong, H. *Org. Lett.* **2018**, *20*, 3225. (x) Yu, L.; Tang, M.-L.; Si, C.-M.; Meng, Z.; Liang, Y.; Han, J.; Sun, X. *Org. Lett.* **2018**, *20*, 4579. (y) Zheng, C.; Wang, Y.; Xu, Y.; Chen, Z.; Chen, G.; Liang, S. H. *Org. Lett.* **2018**, *20*, 4824. (z) Tlahuext-Aca, A.; Candish, L.; Garza-Sanchez, R. A.; Glorius, F. *ACS Catal.* **2018**, *8*, 1715.

(8) The detailed experiments are summarized in the Supporting Information (Figure S1). For selected papers, see: (a) Bahamonde, A.; Melchiorre, P. *J. Am. Chem. Soc.* **2016**, *138*, 8019. (b) Teders, M.; Pitzer, L.; Buss, S.; Glorius, F. *ACS Catal.* **2017**, *7*, 4053. (c) Gorner, H.; Kuhn, H. J. *J. Chem. Soc., Perkin Trans. 2* **1999**, *2*, 2671.




DOI: 10.1021/acs.orglett.8b02670
*Org. Lett.* XXXX, XXX, XXX−XXX