

# Copper-Catalyzed Oxy-Alkynylation of Diazo Compounds with Hypervalent Iodine Reagents

Durga Prasad Hari and Jerome Waser\*

Laboratory of Catalysis and Organic Synthesis, Ecole Polytechnique Fédérale de Lausanne, EPFL SB ISIC LCSO, BCH 4306, 1015 Lausanne, Switzerland

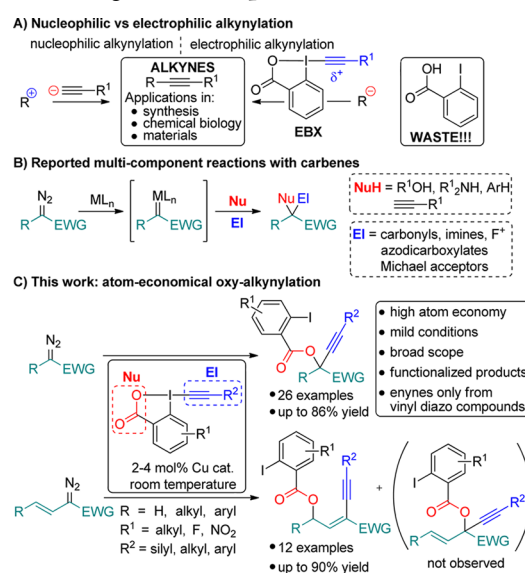
**S** Supporting Information

**ABSTRACT:** Alkynes have found widespread applications in synthetic chemistry, biology, and materials sciences. In recent years, methods based on electrophilic alkylation with hypervalent iodine reagents have made acetylene synthesis more flexible and efficient, but they lead to the formation of one equivalent of an iodoarene as side-product. Herein, a more efficient strategy involving a copper-catalyzed oxy-alkynylation of diazo compounds with ethynylbenziodoxol(on)e (EBX) reagents is described, which proceeds with generation of nitrogen gas as the only waste. This reaction is remarkable for its broad scope in both EBX reagents and diazo compounds. In addition, vinyl diazo compounds gave enynes selectively as single geometric isomers. The functional groups introduced during the transformation served as easy handles to access useful building blocks for synthetic and medicinal chemistry.

The carbon–carbon triple bond is among the most valuable functional groups in organic chemistry because of its versatile reactivity.<sup>1</sup> Alkynes are broadly applied as chemical building blocks for the synthesis of fine chemicals.<sup>2</sup> In past years, they have also gained a lot of interest for applications in biochemistry or material sciences.<sup>1,3</sup> As a result of this growing importance of alkynes, developing more efficient and versatile methods for their synthesis is of fundamental importance. Alkynes are often accessed by the addition of acetylides on electrophilic positions of molecules.<sup>4</sup> However, introducing triple bonds only to electrophilic positions strongly limits the flexibility and efficiency of alkyne synthesis. Major efforts have therefore been made to develop electrophilic alkylation methods, relying on the umpolung of the innate reactivity of acetylenes (Scheme 1A).<sup>5</sup>

Hypervalent iodine reagents such as alkynylidonium salts have been particularly successful for the electrophilic alkylation of nucleophiles.<sup>6</sup> However, the use of alkynylidonium salts is limited due to their low stability. Recently, ethynylbenziodoxol(on)es (EBX)<sup>7a,b</sup> have been introduced as excellent electrophilic reagents for the alkylation of ketoesters,<sup>7c</sup> thiols,<sup>7d</sup> and aromatic C–H bonds using transition metal catalysis,<sup>7e–g</sup> among many other successful transformations.<sup>7h</sup> Nevertheless, the developed methods are often restricted to the transfer of one type of acetylenes (either silyl-, aryl-, or alkyl- substituted). Furthermore, 2-iodobenzoic acid is usually obtained as a stoichiometric byproduct after alkylation, resulting in low

## Scheme 1. Alkynylation Strategies and Multicomponent Reactions Using Diazo Compounds



atom economy.<sup>8</sup> Recently, Greaney and co-workers<sup>9a</sup> and Dauban and co-workers<sup>9b</sup> reported more atom economical transformations based on the use of the formed aryl iodides in cross-coupling reactions with arylidonium salts and  $\text{PhI}(\text{OPiv})_2$ , respectively. With EBX reagents, progress in this area has been limited to a report of Yoshikai and co-workers on the palladium-catalyzed reaction of imines with alkynylbenziodoxolones to give furan derivatives.<sup>10</sup>

To develop more efficient transformations with EBX reagents, we intended to make use of the nucleophilic properties of the formed iodobenzoate side products. In this context, metal carbene species are interesting reactive intermediates, as they display both nucleophilic and electrophilic reactivity on a single carbon atom and can be easily generated from  $\alpha$ -diazo carbonyl compounds.<sup>11</sup> They have been used in a broad range of transformations such as X–H bond insertions, cyclopropanation, ylide formation, and 1,2- migration reactions and have been successfully applied in total synthesis.<sup>12</sup> Recently, research in the area has focused on the development of multicomponent reactions to afford products with high structural diversity, complexity, and atom economy (Scheme 1B).<sup>13</sup> The only

Received: January 16, 2016

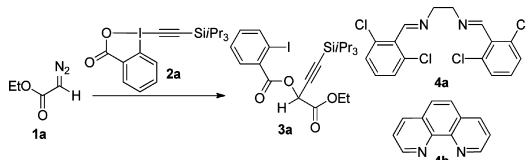
Published: February 12, 2016

approach for the synthesis of alkynes from diazo compounds has been reported by Wang and co-workers for a reaction involving metal carbene migratory insertion with nucleophilic alkynes.<sup>14</sup> We envisioned a different strategy making use of the carboxylate of the EBX reagent as a nucleophile, and the alkyne as an electrophile.

Herein, we report the successful implementation of this strategy, resulting in a highly efficient and atom economical oxy-alkynylation of diazo compounds under mild conditions using a nonexpensive copper catalyst (Scheme 1C). The reaction exhibits a broad scope toward both diazo compounds and EBX-reagents and tolerates many functional groups. It provides access to both secondary and tertiary propargylic alcohol derivatives and can be used for the synthesis of silyl-, aryl-, and alkyl-substituted acetylenes. The iodine atom, the ester, and the triple bond of the product can serve as versatile handles for further transformations. Interestingly, when vinyl diazo compounds were used as starting materials, only 1,4-addition to give enynes was observed.

We first attempted the oxy-alkynylation of ethyl diazoacetate (1a) with 1-[(triisopropylsilyl)ethynyl]-1,2-benziodoxol-3(1H)-one (TIPS-EBX, 2a) using 5 mol % of Rh<sub>2</sub>(OAc)<sub>4</sub> in DCM at 40 °C, but did not obtain the desired product 3a (Table 1, entry 1).

Table 1. Optimization of the Reaction Conditions<sup>a</sup>



entry	catalyst (Xmol %)	solvent (conc.)	time/T (°C)	yield
1	Rh <sub>2</sub> (OAc) <sub>4</sub> (5.0)	DCM (0.1 M)	20 h/40	<5%
2	Cu(OTf) <sub>2</sub> (5.0)	DCM (0.1 M)	20 h/40	19%
3	Cu(CH <sub>3</sub> CN) <sub>4</sub> BF <sub>4</sub> (5.0)	DCM (0.1 M)	20 h/40	24%
4	CuCl (5.0)	DCM (0.1 M)	20 h/40	<5%
5	Cu(OAc) <sub>2</sub> (5.0)	DCM (0.1 M)	20 h/40	<5%
6	PdCl <sub>2</sub> (PPh <sub>3</sub> ) <sub>2</sub> (5.0)	DCM (0.1 M)	2 h/40	<5%
7	AuBr <sub>3</sub> (5.0)	DCM (0.1 M)	18 h/40	<5%
8	Cu(CH <sub>3</sub> CN) <sub>4</sub> BF <sub>4</sub> (5.0)	DCE (0.1 M)	2 h/65	30%
9 <sup>b</sup>	Cu(CH <sub>3</sub> CN) <sub>4</sub> BF <sub>4</sub> (5.0)	DCE (0.1 M)	1 h/65	46%
10 <sup>b</sup>	Cu(CH <sub>3</sub> CN) <sub>4</sub> BF <sub>4</sub> (2.0)	DCE (0.1 M)	1.5 h/65	54%
11 <sup>b</sup>	Cu(CH <sub>3</sub> CN) <sub>4</sub> BF <sub>4</sub> (2.0)	DCE (0.05 M)	2.5 h/65	60%
12 <sup>b,c</sup>	Cu(CH <sub>3</sub> CN) <sub>4</sub> BF <sub>4</sub> (2.0)	DCE (0.05 M)	1 h/RT	86%
13 <sup>b,d</sup>	Cu(CH <sub>3</sub> CN) <sub>4</sub> BF <sub>4</sub> (2.0)	DCE (0.05 M)	20 h/RT	<5%
14 <sup>b</sup>	no catalyst	DCE (0.05 M)	20 h/65	<5%

<sup>a</sup>Reaction conditions: 0.30 mmol ethyldiazoacetate (1a), 0.25 mmol TIPS-EBX (2a). The reaction was run for 20 h or until full conversion of the EBX reagent. Yield after purification by column chromatography. <sup>b</sup>With 0.50 mmol 1a. <sup>c</sup>With 2.5 mol % of 4a. <sup>d</sup>With 2.5 mol % of 4b.

Replacing Rh<sub>2</sub>(OAc)<sub>4</sub> with Cu(OTf)<sub>2</sub> gave the desired product 3a in 19% yield after 20 h at 40 °C (Table 1, entry 2). Product 3a was obtained in 24% yield when Cu(CH<sub>3</sub>CN)<sub>4</sub>BF<sub>4</sub> was used (Table 1, entry 3), whereas the use of other metal catalysts such as CuCl, Cu(OAc)<sub>2</sub>, PdCl<sub>2</sub>(PPh<sub>3</sub>)<sub>2</sub>, and AuBr<sub>3</sub> did not lead to the formation of the desired product 3a (Table 1, entries 4–7). Use of DCE as a solvent at 65 °C gave 3a in 30% yield (Table 1, entry 8). With two equivalents of 1a, the yield could be raised to 46% (Table 1, entry 9). Decreasing the catalyst loading to 2 mol % gave 3a in 54% yield (Table 1, entry 10). Alkyne 3a was then obtained

in 60% yield when the concentration of the reaction was decreased to 0.05 M (Table 1, entry 11). Finally, a major improvement was obtained when using 2.5 mol % of 1,2-diimine 4a as ligand.<sup>15</sup> The yield increased to 86% and the reaction could be performed at room temperature (Table 1, entry 12). In contrast, the reaction did not take place when using 1,10-phenanthroline (4b) as ligand (Table 1, entry 13). In the absence of Cu(CH<sub>3</sub>CN)<sub>4</sub>BF<sub>4</sub>, no product was obtained, demonstrating that the copper catalyst is necessary for the reaction (Table 1, entry 14).

The scope of the reaction was first examined using TIPS-EBX (2a) and a variety of  $\alpha$ -diazo compounds (Figure 1A). *tert*-Butyl and benzyl diazoacetates provided the oxy-alkynylation products 3b and 3c in high yields. The transformation was also successful for disubstituted diazo compounds, leading to products 3d–f with tertiary propargylic centers. Noteworthy, a cyclic diazo compound also afforded the desired product 3g in 80% yield. Derivatives of  $\alpha$ -hydroxy-alkynyl lactones are present in pharmaceutical molecules<sup>16</sup> but have never been synthesized directly from lactones to the best of our knowledge. In addition to  $\alpha$ -diazo esters, several other diazo compounds including 2-diazo-*N,N*-diethylacetamide, ethyl diazomethanesulfonate, and diethyl (diazomethyl)phosphonate underwent the desired transformation in good to high yields (products 3h–j). We then turned our attention to the scope of R-EBX reagents (Figure 1B). Electron-donating and -withdrawing groups were well tolerated on the aryl ring of TIPS-EBX (2a) (products 3k–m). EBX reagents bearing aryl substituents on the alkyne worked efficiently in this transformation, giving products 3n–p in 80–84% yield. Bromide-substituted product 3p, which is useful for further chemical transformations, could be isolated in 83% yield. Several aliphatic EBX reagents bearing functional groups such as a chloro, an azido, and an ether also gave the desired products in moderate to high yields (products 3q–t). A cyclopropyl derived EBX reagent can also be used in this reaction (product 3u). A TMS-alkyne substituted EBX reagent gave product 3v in 75% yield. In addition, ethyl 2-diazopropanoate can also be oxy-alkynylated successfully with aryl-substituted EBX reagents to furnish products 3w and 3x with tertiary propargylic centers in 78% and 72% yield, respectively.

Next, the developed method was applied to the oxy-alkynylation of vinyl diazo compounds (Figure 1C). Controlling the selectivity in the reaction of nucleophiles with vinyl diazo compounds is challenging, as they display electrophilic reactivity at both the carbenoid and the vinylogous center.<sup>17</sup> Gratifyingly, only vinylogous product 6a was obtained as a single geometric isomer when using (*E*)-methyl 2-diazopent-3-enoate (5a) with TIPS-EBX (2a). We were pleased to see that (*E*)-methyl 2-diazohept-3-enoate (5b) and cyclic diazo compounds 5c and 5d could be used to give the desired vinylogous products 6b, 6c, and 6d in good to high yields.<sup>18</sup> Various R-EBX reagents were then examined. TIPS-EBX reagents having substituents on the aromatic ring led to the desired products 6e and 6f in high yields. The reaction was also successful with aryl-substituted EBX reagents, and products 6g and 6h were obtained in 82% and 75% yield, respectively. Substituents containing a long alkyl chain, a chloro, and a cyclopropyl functional group were well tolerated in this reaction (products 6i–k). A TMS-alkyne substituted EBX reagent gave the vinylogous product 6l in 72% yield.

Modification of steroidal drugs provides an efficient route for the fine-tuning of their biological activity. Therefore, our method was applied to the late-stage oxy-alkynylation of diazo derivatives 7 and 8 of steroids,<sup>19</sup> which could be smoothly converted to the desired products 9 and 10 in 82% and 75% yield, respectively

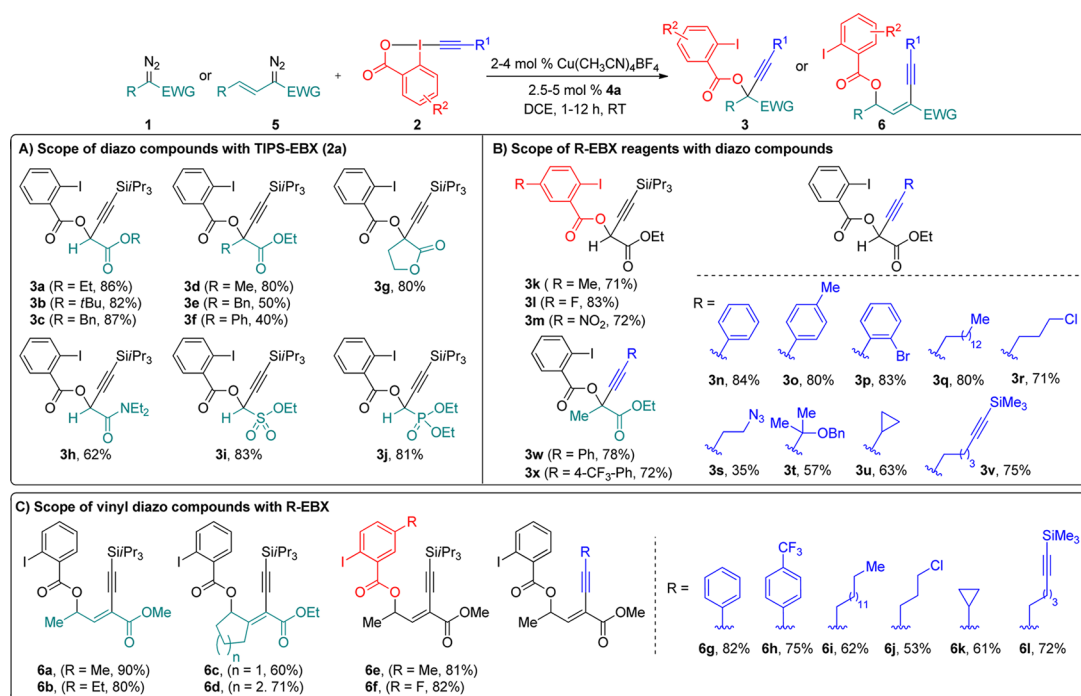
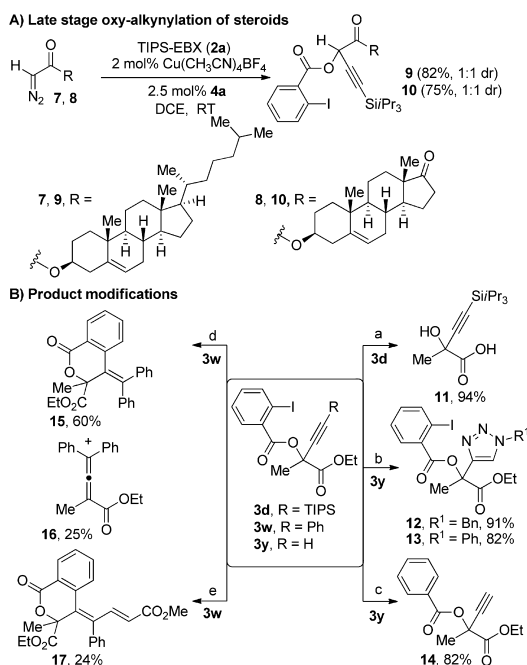


Figure 1. Scope of the copper-catalyzed oxy-alkynylation of diazo compounds with EBX reagents.

(Scheme 2A). This transformation highlights the chemo-selectivity of the method in the presence of carbon–hydrogen bonds, olefins, and carbonyls, which can react with carbene intermediates.<sup>20</sup>

The obtained products contain three valuable functional groups: an alkyne, an iodide, and an ester. Oxy-alkynylated

### Scheme 2. Late Stage Reaction and Product Modifications<sup>a</sup>



<sup>a</sup>Reaction conditions: (a) K<sub>2</sub>CO<sub>3</sub>, EtOH; (b) R<sup>1</sup>N<sub>3</sub>, 20 mol % CuSO<sub>4</sub>·5H<sub>2</sub>O, sodium ascorbate, triazole ligand, *t*BuOH/H<sub>2</sub>O; (c) 2.5 mol % *fac*-Ir(ppy)<sub>3</sub>, NBu<sub>3</sub>, HCO<sub>2</sub>H, blue LED, MeCN; (d) 5 mol % Pd(PPh<sub>3</sub>)<sub>4</sub>, K<sub>2</sub>CO<sub>3</sub>, PhB(OH)<sub>2</sub>, DMF; (e) ethyl acrylate, 5 mol % Pd(PPh<sub>3</sub>)<sub>4</sub>, NEt<sub>3</sub>, DMF.

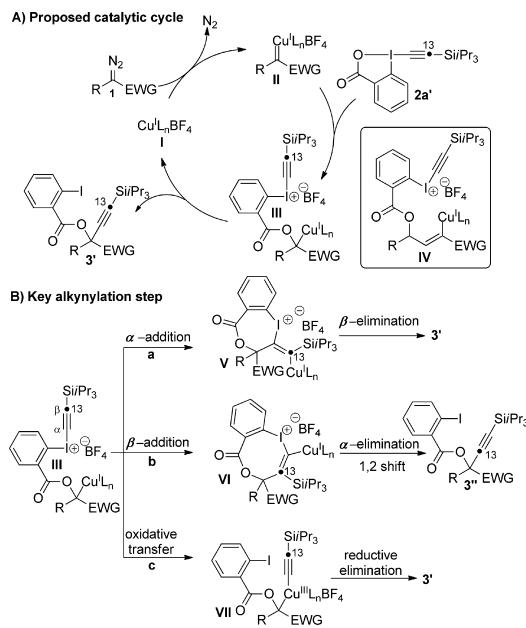
products 3a, 3d, and 3w were synthesized on gram scale in 91%, 84%, and 79% yield, respectively. Ester 3d could be readily hydrolyzed, affording the alkyne substituted  $\alpha$ -hydroxy acid 11 in 94% yield (Scheme 2B). Copper-catalyzed cycloaddition of terminal alkyne 3d, with benzyl and phenyl azides 3y, obtained by desilylation of 3d, with benzyl and phenyl azides gave triazoles 12 and 13 in high yields. Deiodination of 3y was achieved using visible light photoredox catalysis to give product 14 in 82% yield.<sup>21</sup> Isocoumarin derivative 15 could be synthesized using a domino carbopalladation/Suzuki cascade reaction<sup>22</sup> in 60% yield from 3w. Tetra-substituted allene 16 was also obtained as a side product in the coupling reaction. Finally, a domino carbopalladation/Heck cascade reaction was also possible to furnish product 17 in 24% yield from 3w.

Based on literature reports<sup>5,13,17</sup> and our own results, we propose a tentative mechanism for the reaction (Scheme 3A). The Cu(I) catalyst I first reacts with diazo compound 1 to form copper-carbene intermediate II. Then the carboxylate group of EBX reagent 2 adds to carbene intermediate II to form organocopper species III. Finally, intramolecular alkyne transfer gives product 3. For vinyl diazo compound 5, conjugate addition on the formed carbene intermediate would give organocopper species IV, which affords enyne product 6 as a single geometric isomer after alkyne transfer. For the alkyne transfer step, several mechanisms could be envisaged (Scheme 3B): nucleophilic attack on either the  $\alpha$  or  $\beta$  position of the alkynyliodonium salt (pathways a and b), or oxidative alkyne transfer to copper (pathway c). In the case of  $\alpha$ -addition,  $\beta$ -elimination of the iodine would lead directly to the product from the formed intermediate V. Alternatively, a concerted reaction could also be envisaged.<sup>7d</sup> However,  $\beta$ -addition would furnish first a vinylidene intermediate via  $\alpha$ -elimination on addition product VI. A fast 1,2-silicon shift would then lead to product 3.

When <sup>13</sup>C labeled TIPS-EBX reagent 2a' was used in the reaction, product 3' without 1,2-shift of the silyl group was obtained exclusively, which indicated that addition on the  $\beta$  position is less probable. However, oxidative alkyne transfer to



## Scheme 3. Proposed Mechanism for Oxy-Alkynylation



give copper(III) intermediate VII, followed by reductive elimination (pathway c) would also lead to the observed product 3'. Consequently, further investigations will be needed to elucidate the mechanism of the alkyne-transfer step.

In conclusion, we have developed an atom economical oxy-alkynylation of diazo compounds using EBX reagents. The reaction protocol is highly practical and characterized by mild reaction conditions, high yields, and the use of an inexpensive copper catalyst. A remarkably broad range of R-EBX reagents and diazo compounds were well tolerated in this transformation. In the case of vinyl diazo compounds, we obtained enyne products as single olefin isomers in high yields. The obtained products were efficiently transformed into useful building blocks such as  $\alpha$ -hydroxy acids, triazoles, and isocoumarins. Further investigation using other hypervalent iodine reagents, studies to confirm the proposed mechanism of the reaction, and the development of an asymmetric version of the transformation are currently ongoing in our laboratories.

## ■ ASSOCIATED CONTENT

### Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/jacs.6b00278.

Experimental procedures (PDF)

Analytical data (CIF)

## ■ AUTHOR INFORMATION

### Corresponding Author

\*jerome.waser@epfl.ch

### Notes

The authors declare no competing financial interest.

## ■ ACKNOWLEDGMENTS

We thank European Research Council (ERC; Starting Grant iTools4MC, number 334840) and the EPFL for financial support. We thank Dr. Scopelliti Rosario from ISIC-EPFL for the X-ray studies.

## ■ REFERENCES

- (1) Diederich, F.; Stang, P. J.; Tykwinski, R. R. *Acetylene Chemistry: Chemistry, Biology and Material Science*; Wiley-VCH: Weinheim, 2005.
- (2) (a) Trost, B. M.; Li, C. J. *Modern Alkyne Chemistry: Catalytic and Atom-Economic Transformations*; Wiley: Weinheim, 2014. (b) Schobert, H. *Chem. Rev.* **2014**, *114*, 1743.
- (3) (a) Rostovtsev, V. V.; Green, L. G.; Fokin, V. V.; Sharpless, K. B. *Angew. Chem., Int. Ed.* **2002**, *41*, 2596. (b) Prescher, J. A.; Bertozzi, C. R. *Nat. Chem. Biol.* **2005**, *1*, 13. (c) Lutz, J.-F. *Angew. Chem., Int. Ed.* **2007**, *46*, 1018. (d) Meldal, M.; Tornøe, C. W. *Chem. Rev.* **2008**, *108*, 2952.
- (4) (a) Trost, B. M.; Weiss, A. H. *Adv. Synth. Catal.* **2009**, *351*, 963. (b) Chinchilla, R.; Najera, C. *Chem. Rev.* **2007**, *107*, 874.
- (5) Brand, J. P.; Waser, J. *Chem. Soc. Rev.* **2012**, *41*, 4165.
- (6) Zhdankin, V. V.; Stang, P. J. *Tetrahedron* **1998**, *54*, 10927.
- (7) (a) Ochiai, M.; Masaki, Y.; Shiro, M. *J. Org. Chem.* **1991**, *56*, 5511. (b) Zhdankin, V. V.; Kuehl, C. J.; Krasutsky, A. P.; Bolz, J. T.; Simonsen, A. J. *J. Org. Chem.* **1996**, *61*, 6547. (c) Fernandez Gonzalez, D.; Brand, J. P.; Waser, J. *Chem. - Eur. J.* **2010**, *16*, 9457. (d) Frei, R.; Wodrich, M. D.; Hari, D. P.; Borin, P. A.; Chauvier, C.; Waser, J. *J. Am. Chem. Soc.* **2014**, *136*, 16563. (e) Brand, J. P.; Charpentier, J.; Waser, J. *Angew. Chem., Int. Ed.* **2009**, *48*, 9346. (f) Feng, C.; Loh, T.-P. *Angew. Chem., Int. Ed.* **2014**, *53*, 2722. (g) Xie, F.; Qi, Z.; Yu, S.; Li, X. *J. Am. Chem. Soc.* **2014**, *136*, 4780. For a review, see: (h) Kaschel, J.; Werz, D. B. *Angew. Chem., Int. Ed.* **2015**, *54*, 8876.
- (8) Trost, B. M. *Science* **1991**, *254*, 1471.
- (9) (a) Modha, S. G.; Greaney, M. F. *J. Am. Chem. Soc.* **2015**, *137*, 1416. (b) Buendia, J.; Darses, B.; Dauban, P. *Angew. Chem., Int. Ed.* **2015**, *54*, 5697.
- (10) Lu, B.; Wu, J.; Yoshikai, N. *J. Am. Chem. Soc.* **2014**, *136*, 11598.
- (11) Ford, A.; Miel, H.; Ring, A.; Slattery, C. N.; Maguire, A. R.; McKervy, M. A. *Chem. Rev.* **2015**, *115*, 9981.
- (12) (a) Davies, H. M. L.; Manning, J. R. *Nature* **2008**, *451*, 417. (b) Davies, H. M. L.; Denton, J. R. *Chem. Soc. Rev.* **2009**, *38*, 3061. (c) Davies, H. M. L.; Morton, D. *Chem. Soc. Rev.* **2011**, *40*, 1857. (d) Parr, B. T.; Davies, H. M. L. *Nat. Commun.* **2014**, *5*, 4455. (e) Zhao, X.; Zhang, Y.; Wang, J. *Chem. Commun.* **2012**, *48*, 10162.
- (13) (a) Huang, H.; Guo, X.; Hu, W. *Angew. Chem., Int. Ed.* **2007**, *46*, 1337. (b) Hu, W.; Xu, X.; Zhou, J.; Liu, W.-J.; Huang, H.; Hu, J.; Yang, L.; Gong, L.-Z. *J. Am. Chem. Soc.* **2008**, *130*, 7782. (c) Qiu, H.; Li, M.; Jiang, L.-Q.; Lv, F.-P.; Zan, L.; Zhai, C.-W.; Doyle, M. P.; Hu, W.-H. *Nat. Chem.* **2012**, *4*, 733. (d) Guo, X.; Hu, W. *Acc. Chem. Res.* **2013**, *46*, 2427. (e) Zhang, D.; Zhou, J.; Xia, F.; Kang, Z.; Hu, W. *Nat. Commun.* **2015**, *6*, 5801. (f) Zhou, C.-Y.; Wang, J.-C.; Wei, J.; Xu, Z.-J.; Guo, Z.; Low, K.-H.; Che, C.-M. *Angew. Chem., Int. Ed.* **2012**, *51*, 11376. (g) Chen, D.-F.; Zhao, F.; Hu, Y.; Gong, L.-Z. *Angew. Chem., Int. Ed.* **2014**, *53*, 10763. (h) Wu, M.-Y.; He, W.-W.; Liu, X.-Y.; Tan, B. *Angew. Chem., Int. Ed.* **2015**, *54*, 9409. (i) Chen, G.; Song, J.; Yu, Y.; Luo, X.; Li, C.; Huang, X. *Chem. Sci.* **2016**, DOI: 10.1039/C5SC04237B.
- (14) (a) Xia, Y.; Feng, S.; Liu, Z.; Zhang, Y.; Wang, J. *Angew. Chem., Int. Ed.* **2015**, *54*, 7891. (b) Wang, C.; Ye, F.; Wu, C.; Zhang, Y.; Wang, J. *J. Org. Chem.* **2015**, *80*, 8748.
- (15) Ma, M.; Peng, L. L.; Li, C. K.; Zhang, X.; Wang, J. B. *J. Am. Chem. Soc.* **2005**, *127*, 15016.
- (16) Blaquièrre, N.; Burch, J.; Feng, J. A.; Hu, B.; Lin, X.; Staben, S.; Wu, G.; Yuen, P. W. Alkynyl alcohols and methods of use. F. Hoffmann-La Roche Ag, Genentech, Inc., WO 2015025026 A1, 2015.
- (17) Hansen, J. H.; Davies, H. M. L. *Chem. Sci.* **2011**, *2*, 457.
- (18) The structure of 6c was unambiguously determined by X-ray crystallographic analysis (see the Supporting Information).
- (19) Toma, T.; Shimokawa, J.; Fukuyama, T. *Org. Lett.* **2007**, *9*, 3195.
- (20) Doyle, M. P.; Davies, S. B.; May, E. J. *J. Org. Chem.* **2001**, *66*, 8112.
- (21) Nguyen, J. D.; D'Amato, E. M.; Narayanam, J. M. R.; Stephenson, C. R. J. *Nat. Chem.* **2012**, *4*, 854.
- (22) Guo, L.-N.; Duan, X.-H.; Hu, J.; Bi, H.-P.; Liu, X.-Y.; Liang, Y.-M. *Eur. J. Org. Chem.* **2008**, *2008*, 1418.