Organic LETTERS

Letter

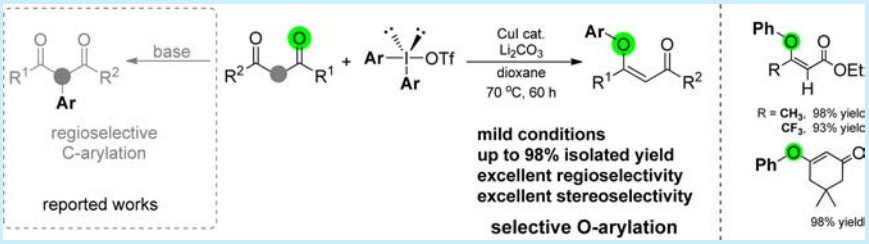
pubs.acs.org/OrgLett

Copper-Catalyzed Regio- and Stereoselective O-Arylation of Enolates

Ze-Feng Xu, Chen-Xin Cai, Min Jiang, and Jin-Tao Liu*

Key Laboratory of Organofluorine Chemistry, Shanghai Institute of Organic Chemistry, Chinese Academy of Science, 345 Lingling Road, Shanghai 200032, China

Supporting Information

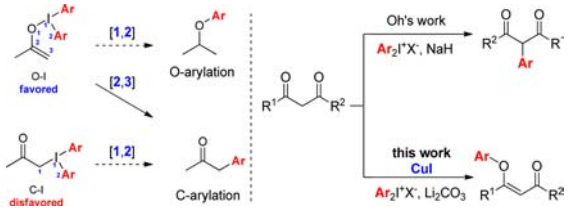


ABSTRACT: Copper-catalyzed O-arylation of enolates with diaryliodonium salts as arylating reagents was realized successfully. As important building blocks, β-aryloxy carbonyl compounds were obtained in up to 98% yield under mild conditions, and complete control of O-arylation and *Z*-stereoselectivity were achieved. The origin of the selectivity was also discussed.

The regioselective control of the C-functionalization or O-functionalization of enolate is a historical research area and still very attractive.[1] The regioselectivity is sensitive to both reaction conditions and the properties of enolate and electrophile. In general, the softer electrophiles react more easily with the carbon center, whereas the harder electrophiles have stronger affinity to the oxygen center.[2] Although the control of the regioselective functionalization of the C/O center has been achieved for some reactions,[3] such as C/O-alkylation,[3a,b] C/O-fluoroalkylation,[3c,d] and C/O-acylation,[3e,g] and the C-arylation reaction has also been developed very well,[4] no regioselective O-arylation of enolates has been reported. Considering the importance of aryl ethers, especially the existence of β-aryloxy carbonyl moiety in many useful molecules,[5] it would be of great significance to develop a practical method for the regioselective O-arylation of enolates.

As an appealing arylating reagent, diaryliodonium salt **1**,[6] easily prepared in one step from commercially available materials, is air- and moisture-stable and has been used as an efficient arylating reagent in the arylation of O-center,[7a−g] such as alcohols, phenols, carboxylates and hydroxylamines, and the arylation of C-center,[7g−t] such as carbonyl compounds and their derivatives. Olofsson and co-workers reported that in the C-arylation reaction of enolate, [2,3] rearrangement of the O−I intermediate was slightly favored compared to the [1,2] rearrangement of the C−I intermediate[7s] (Scheme 1). However, Gaunt and co-workers reported that the catalyst is very important to the regioselectivity of the arylation reaction of diaryliodonium salt.[8] For example, using **1** as the arylating reagent, Pd salts could catalyze the C-2 arylation of indol, whereas Cu salts achieved the C-3 arylation. In the case of acyl-protected aniline, the *ortho*-arylation products were obtained with Pd catalysts, while Cu salts promoted the *meta*-arylation. In 1999, Oh and co-workers reported the efficient C-arylation of enolate derived from 1,3-dicarbonyl compounds using diaryliodonium salt as arylating reagent and sodium hydride as base (Scheme 1).[7l]

Scheme 1. Proposal of O-Arylation of Enolates



Considering the important role of catalyst in the regioselective arylation reaction involving diaryliodonium salt, we assumed that if a proper metal catalyst was used, the regioselectivity of the reaction might reverse and the O-arylation product would be obtained regioselectively (Scheme 1). This would provide a facile synthesis of β-aryloxy-α,β-unsaturated carbonyl compounds which were obtained by the addition reaction of phenols and propiolates only.[5h] Herein, we report our realization of the copper-catalyzed regioselective O-arylation of enolates derived from 1,3-dicarbonyl compounds with diaryliodonium salts.

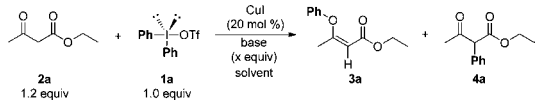
In our initial experiment, ethyl acetoacetate (**2a**) was chosen as a model substrate to react with Ph_2IOTf (**1a**) in the presence of CuI (20 mol %), proline (40 mol %), and Cs_2CO_3 (4.0 equiv) in DMSO at 40 °C (Table 1, entry 1).[4g] Unfortunately, no expected O-arylation product **3a** was formed, and the C-arylation product **4a** was generated in 52% yield after 24 h. When Li_2CO_3 was used as base, the yield of **4a** was reduced and the desired product **3a** was obtained in 3% yield (entry 2).

Without proline, the yield of **3a** was increased to 21% at 60 °C (entry 3). Further studies indicated that the amount of Li_2CO_3

Received: April 18, 2014
Published: June 19, 2014

   dx.doi.org/10.1021/ol501434d | *Org. Lett.* 2014, 16, 3436−3439

Table 1. Optimization of O-Arylation of Ethyl Acetoacetate[a]



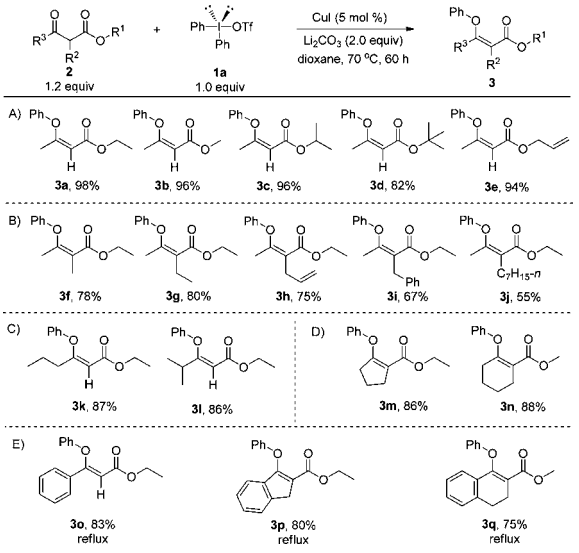
entry	base (x)	solvent	temp (°C)	time (h)	yield[b] (%) 3a	4a
1[c]	Cs_2CO_3 (4.0)	DMSO	40	24		52
2[c]	Li_2CO_3 (4.0)	DMSO	40	24	3	5
3	Li_2CO_3 (4.0)	DMSO	60	24	21	3
4	Li_2CO_3 (3.0)	DMSO	60	24	27	2
5	Li_2CO_3 (3.0)	DMF	60	24	12	18
6	Li_2CO_3 (3.0)	DMAC	60	24	8	2
7	Li_2CO_3 (3.0)	NMP	60	24	11	4
8	Li_2CO_3 (3.0)	MeCN	60	24	6	trace
9	Li_2CO_3 (3.0)	dioxane	60	36	79	3
10	Li_2CO_3 (3.0)	dioxane	70	36	80	trace
11	Li_2CO_3 (2.0)	dioxane	70	36	84	trace
12	Li_2CO_3 (1.0)	dioxane	70	36	75	trace
13[d]	Li_2CO_3 (2.0)	dioxane	70	48	83	trace
14[e]	Li_2CO_3 (2.0)	dioxane	70	48	87	trace
15[f]	Li_2CO_3 (2.0)	dioxane	80	48	5	
16[e]	Li_2CO_3 (2.0)	dioxane	80	48	78	trace
17[e]	**Li_2CO_3 (2.0)**	**dioxane**	**70**	**60**	**98[g]**	**N.D.**
18[h]	Li $_2CO_3$ (2.0)	dioxane	70	60	19	3
19[i]	Li_2CO_3 (2.0)	dioxane	70	60	68	11
20[j]	Li_2CO_3 (2.0)	dioxane	70	60	trace	trace
21[e]	Na_2CO_3 (2.0)	dioxane	70	60	24	5
22[e]	K_2CO_3 (2.0)	dioxane	70	60	6	10

[a]Reaction scale: **1a** (0.32 mmol, 1.0 equiv), **2a** (0.38 mmol, 1.2 equiv), solvent (1.0 mL). [b]Determined by ^{1}H NMR with 1,3,5-trimethylbenzene as internal standard. [c]Proline (40 mol %) was used as ligand. [d]CuI (10 mol %) was used as catalyst. [e]CuI (5 mol %) was used as catalyst. [f]No CuI was used. [g]Isolated yield. [h]CuCl (5 mol %) was used as catalyst. [i]$Cu(OTf)_2$ (5 mol %) was used as catalyst. [j]$Pd(OAc)_2$ (5 mol %) was used as catalyst. temp = temperature, time = reaction time, DMSO = dimethyl sulfoxide, DMF = dimethylformamide, DMA = dimethylacetamide, NMP = *N*-methyl-2-pyrrolidinone, N.D. = not determined.

could be reduced to 3.0 equiv (27% yield, entry 4). Examination of the solvent effect (entries 5−9) revealed that when dioxane was used as solvent, **3a** was obtained in 79% yield and **4a** was formed in only 3% yield (entry 2). Further screening of the reaction conditions using dioxane as solvent (entries 10−17) showed that 98% isolated yield of **3a** was achieved at 70 °C in the presence of 5 mol % of CuI and 2.0 equiv of Li_2CO_3 for 60 h, as indicated in entry 17, which was selected as the optimal reaction conditions. It is worth mentioning that only 5% yield of **3a** was obtained without CuI (entry 15), and other catalysts such as CuCl, $Cu(OTf)_2$, and $Pd(OAc)_2$ gave poor results (entries 18−20), demonstrating the important role of CuI in this reaction. Furthermore, poor performance was also observed with other bases, such as Na_2CO_3 and K_2CO_3, under the optimal conditions (entries 21 and 22). The stereochemistry of the double bond in **3a** was determined as *Z* by comparing its analytical data with those in the literature.[9]

With the optimized conditions in hand, the scope of substrates **2** was evaluated (Scheme 2). In general, the reaction was extremely regio- and stereoselective. Only O-arylation occurred, and the *Z*-isomer was obtained as the sole product. Although the substituents in β-ketonesters have different influences on the

Scheme 2. O-Phenylation of Enolates



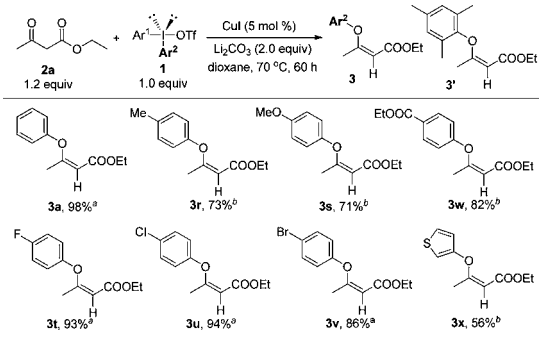
yields of the reaction, the excellent selectivity remained unaffected. When R^2 = H, R^3 = Me, and R^1 = Et, Me, or *i*-Pr, the corresponding products were obtained in excellent yields (**3a−c** 96−98%, Scheme 2A). Good yields were also achieved with *tert*-butyl (**3d**, 88%) and allyl (**3e**, 94%) acetoacetate, indicating that the steric effect of the R^1 substituent had little influence on the reaction because it was far away from the reaction center. In contrast, the R^2 substituent had much more influence on the reaction. As shown in Scheme 2B, lower yields were obtained when a substituent was introduced to the α-carbon of substrate **2** (**3f−h**, 75−88%), and the yield dropped sharply with the increase of the steric hindrance of substituent (**3i,j**, R^2 = Bn, *n*-C_7H_{15}). Substituent R^3 also had some influence on the yield of the reaction. When R^3 = Pr or *i*-Pr, the yields of **3k** and **3l** were a little lower than that of **3a** (Scheme 2C). Furthermore, the reaction of cyclic substrate also proceeded well to give the corresponding products in good yields (86−88%, Scheme 2D).

Since the β-aryl, β-aryloxycarbonyl moiety is a very important scaffold in many active molecules, the O-arylation of substrate **2** with an aryl substituent in the β-position was also investigated. However, the reaction of **2o** (R^1 = Et, R^2 = H, R^3 = Ph) was very slow, and less than 5% yield was achieved in 60 h under the optimal reactions. Carrying out the reaction under reflux improved the yield of **3o** to 83% (Scheme 2E). Under these conditions, **3p** and **3q** were prepared in 80% and 75% yield, respectively (Scheme 2E). Obviously, aryl substituents decreased the reactivity of enolates to some extent.

Next, a variety of diaryliodonium salts **1** were tested in the reaction (Scheme 3). With symmetrical diaryliodonium salts, the reaction worked very well, and good to excellent yields were achieved (86−98%). In the case of unsymmetrical diaryliodonium salts, even though the dummy aryl 2,4,6-trimethylphenyl (Mes-) was utilized, the selectivity of the aryl transfer was not as good as reported in other reactions.[8a,b,10] Therefore, the yields of the desired products were relatively lower (71−82%) and **3′** was obtained as a byproduct. However, these compounds could be prepared in high yields using the corresponding symmetric salts, as illustrated by a comparison of the yields for some products obtained from symmetric and unsymmetric salts, respectively (see the Supporting Information). Diaryliodonium salt containing a 3-thiophene-yl group also behaved well to give

dx.doi.org/10.1021/ol501434d | *Org. Lett.* 2014, 16, 3436−3439

Scheme 3. O-Arylation of Ethyl Acetoacetate

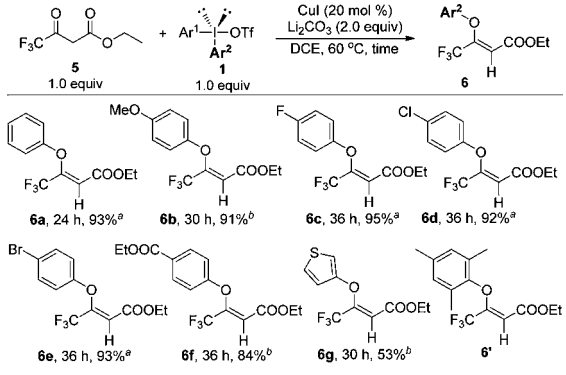


the desired product **3x** in 56% yield. In all reactions, only O-arylation products with a *Z*-configuration were formed selectively.

The synthesis of organofluorine compounds has been a consistent interest in our group. Because of the high electronegativity, hydrophobicity, metabolic activity, and bioavailability, fluorinated compounds, especially trifluoromethylated compounds, have recently attracted significant interest and become very important synthetic targets in laboratories and industries.[11] Among them, compounds containing the 3,3,3-trifluoropropenyl ($CF_3C{=}C$) founctional group[12] have found important applications in various fields such as medicine, pharmaceuticals, and functional materials.[11] Therefore, the O-arylation reaction of ethyl trifluoroacetoacetate (**5**) was investigated. Under the above conditions, however, compound **5** decomposed owing to defluorination. Fortunately, further optimization of reaction conditions showed that the reaction occurred smoothly in DCE (1,2-dichloroethane) at 60 °C, and the desired O-arylation product **6a** was obtained in 93% yield selectively. The structure and configuration of **6a** was determined according to the analytical data and the work of Laurent (see details in the Supporting Information).[13]

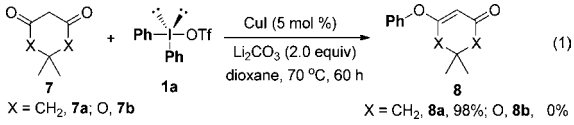
We further examined the scope of diaryliodonium salts in the O-arylation reaction of **5**. As shown in Scheme 4, the reaction

Scheme 4. O-Arylation of Ethyl 4,4,4-Trifluoroacetoacetate.



gave the expected products in high yields (**6a,c**−**e**) with symmetrical diaryliodonium salts ($Ar^1 = Ar^2$), although the reactivity of electron-deficient ones was a little lower and longer reaction time was required. For unsymmetrical diaryliodonium salts containing the dummy aryl group (Ar^1 = Mes),[8a,b,10] product **6b** with a *p*-methoxyl substituent was obtained in 91% yield. In the case of electron-deficient aryl groups, the yield of the corresponding product decreased a little bit because of the formation of byproduct **6′** (**6f** 84%). Moderate yields were obtained with diaryliodonium salts containing a 3-thiophene-yl group (**6g** 53%).

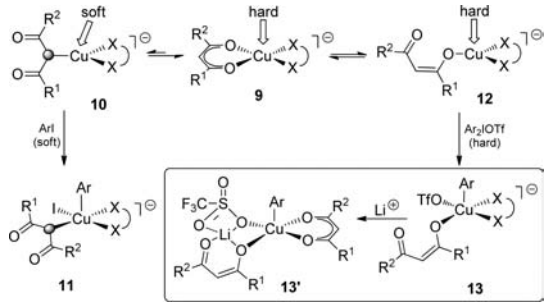
Cyclic dicarbonyl substrates were also tested under the standard conditions (eq 1). Although the corresponding C-



arylation products (monoarylated product and diarylated product) were obtained as the major products in the absence of copper catalyst as reported,[7g] cyclic 5,5-dimethylcyclohexane-1,3-dione (**7a**) was an appropriate substrate for this reaction, and its O-arylation product **8a** was obtained in 98% yield. However, the cyclic Meldrum's acid (**7b**) failed to afford the desired product after 60 h, and **7b** decomposed completely.[7i]

On the basis of the above results and those reported in the literature,[14] a possibility for the controlling mode of the high selectivity of this reaction was proposed as outlined in Scheme 5.

Scheme 5. Discussion of O-Arylation Selectivity of Enolate



Both Hartwig and Lei pointed out that species **9** is the initial intermediate in copper-catalyzed C-arylation, and there is an equilibrium between anionic species **9** and C-bounded species **10**. The addition of iodoarene (ArI) to species **10** generates another Cu(III) species **11**, which undergoes a reductive elimination to give the C-arylation product. It is inferred that the softer copper center in species **10** would be easier to react with the soft reagent ArI to generate intermediate **11**, resulting in the formation of the C-arylation product. In this work, Ar_2IOTf is a harder reagent compared with ArI and prefers to add to the harder copper center in intermediate **12** to give intermediate **13**. Reductive elimination of **13** affords the O-arylation product. Regarding the important role of lithium cation in this regioselective reaction as showed in Table 1 (entries 17, 21, and 22), it is assumed that lithium cation might act as a critical countercation in the intermediates in the reaction. For example, it might coordinate with oxygen atoms in both TfO group and the carbonyl compound in intermediate **13**, giving a more stable species **13′**. This also helps to achieve the high *Z*-stereoselectivity of the reaction.

In summary, a copper-catalyzed O-arylation reaction of enolates with diaryliodonium salts as arylating reagents has been developed. The features of this protocol are as follows: (1) the reaction is very efficient with up to 98% yield; (2) both the regio- and stereoselectivity are excellent, and only O-arylation product with *Z*-configuration was obtained; (3) the reaction takes place under mild conditions and tolerates many functional groups, making it possible to further functionalize the products and prepare more complicated compounds. These features

dx.doi.org/10.1021/ol501434d | Org. Lett. 2014, 16, 3436−3439

demonstrate the synthetic potential of this protocol, and we believe that it will find many applications in organic synthesis.

■ ASSOCIATED CONTENT

Supporting Information

Complete experimental details, spectral data, and copies of ^{1}H NMR, ^{19}F NMR, and ^{13}C NMR spectra for new compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: jtliu@sioc.ac.cn.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

Financial support from the National Natural Science Foundation of China (No. 21172243) is gratefully acknowledged.

■ REFERENCES

(1) (a) Stork, G.; Hudrlik, P. F. *J. Am. Chem. Soc.* **1968**, *90*, 4464−4465. (b) House, H. O.; Czuba, L. J.; Gall, M.; Olmstead, H. D. *J. Org. Chem.* **1969**, *34*, 2324−2336. (c) Brown, C. A. *J. Org. Chem.* **1974**, *39*, 3913−3918. (d) Reutov, O. A.; Beletskaya, I. P.; Kurts, A. L. *Ambident Anions*; Springer: New York, 1983. (e) Eames, J. Acid−base Properties of Enols and Enolates. In *Chemistry of Metal Enolates*; ZabickyL., Ed.; Wiley-VCH: Weinheim, 2009; Part 1, pp 411−460.

(2) Damoun, S.; Van de Woude, G.; Choho, K.; Geerlings, P. *J. Phys. Chem. A* **1999**, *103*, 7861−7866 and references therein.

(3) Selected examples for regioselective C/O-functionalization: (a) Collins, D. J.; Choo, G. L. P.; Obrist, H. *Aust. J. Chem.* **1990**, *43*, 617−622. (b) Midland, M. M.; Koops, R. W. *J. Org. Chem.* **1990**, *55*, 5058−5065. (c) Noritake, S.; Shibata, N.; Nakamura, S.; Toru, T.; Shiro, M. *Eur. J. Org. Chem.* **2008**, 3465−3468. (d) Nomura, Y.; Tokunaga, E.; Shibata, N. *Angew. Chem., Int. Ed.* **2011**, *50*, 1885−1889. (e) Payne, J. E.; Bonnefous, C.; Hassig, C. A.; Symons, K. T.; Guo, X.; Nguyen, P.-M.; Annable, T.; Wash, P. L.; Hoffman, T. Z.; Rao, T. S.; Shiau, A. K.; Malecha, J. W.; Noble, S. A.; Hager, J. H.; Smith, N. D. *Bioorg. Med. Chem. Lett.* **2008**, *18*, 6093−6096. (f) Kislyi, V. P.; Kurykin, M. A.; Grinberg, V. A.; Kagramanov, N. D.; Semenov, V. V. *Russ. Chem. Bull.* **1996**, *45*, 2800−2803. (g) Kumar, G. S.; Maheswari, C. U.; Kumar, R. A.; Kantam, M. L.; Reddy, K. R. *Angew. Chem., Int. Ed.* **2011**, *50*, 11748−11751.

(4) (a) Muratake, H.; Nakai, H. *Tetrahedron Lett.* **1999**, *40*, 2355−2358. (b) Martín, R.; Buchwald, S. L. *Angew. Chem., Int. Ed.* **2007**, *46*, 8108−8111. (c) Vo, G. C.; Hartwig, J. F. *Angew. Chem., Int. Ed.* **2008**, *47*, 2127−2130. (d) Liao, X.; Weng, Z.; Hartwig, J. F. *J. Am. Chem. Soc.* **2008**, *130*, 195−200. (e) Taylor, A. M.; Altman, R. A.; Buchwald, S. L. *J. Am. Chem. Soc.* **2009**, *131*, 9900−9901. (f) Hennessy, E. J.; Buchwald, S. L. *Org. Lett.* **2001**, *4*, 269−272. (g) Xie, X.; Cai, G.; Ma, D. *Org. Lett.* **2006**, *7*, 4693−4695. (h) Guo, J.; Dong, S.; Zhang, Y.; Kuang, Y.; Liu, X.; Lin, L.; Feng, X. *Angew. Chem., Int. Ed.* **2013**, *52*, 10245−10249.

(5) (a) Dai, J.; Krohn, K.; Draeger, S.; Schulz, B. *Eur. J. Org. Chem.* **2009**, *10*, 1564−1569. (b) East, S. P.; Shao, F.; Williams, L.; Joullie, M. M. *Tetrahedron* **1998**, *54*, 13371−13390. (c) Kinoshita, E.; Ozawa, Y.; Aishima, T. *J. Agric. Food Chem.* **1997**, *45*, 3753−3759. (d) Taylor, H. F.; Wain, R. L. *Ann. Appl. Biol.* **1978**, *89*, 271−275. (e) Gier, D. W.; Wasleski, D. M. U.S. Patent 3,738,823, 1973. (f) Miles, W. H.; Fialcowitz, E. J.; Halstead, E. S. *Tetrahedron* **2001**, *57*, 9925−9929. (g) Levai, A.; Ott, J.; Snatzke, G. *Monatsh. Chem.* **1992**, *123*, 919−930. (h) Glorius, F.; Neuburger, M.; Pfaltz, A. *Helv. Chim. Acta* **2001**, *84*, 3178−3196.

(6) (a) Merritt, E. A.; Olofsson, B. *Angew. Chem., Int. Ed.* **2009**, *48*, 9052−9070. (b) Bielawski, M.; Aili, D.; Olofsson, B. *J. Org. Chem.* **2008**, *73*, 4602−4607. (c) Bielawski, M.; Zhu, M.; Olofsson, B. *Adv. Synth. Catal.* **2007**, *349*, 2610−2618. (d) Kitamura, T.; Matsuyuki, J.; Nagata, K.; Furuki, R.; Taniguchi, H. *Synthesis* **1992**, 945−946. (e) Bielawski, M.; Malmgren, J.; Pardo, L. M.; Wikmark, Y.; Olofsson, B. *Chemistry Open* **2014**, *3*, 19−22.

(7) For the arylation of the O-center, see: (a) Jalalian, N.; Petersen, T. B.; Olofsson, B. *Chem.—Eur. J.* **2012**, *18*, 14140−14149. (b) Jalalian, N.; Ishikawa, E. E.; Silva, L. F.; Olofsson, B. *Org. Lett.* **2011**, *13*, 1552−1555. (c) Beringer, F. M.; Brierley, A.; Drexler, M.; Gindler, E. M.; Lumpkin, C. C. *J. Am. Chem. Soc.* **1953**, *75*, 2708−2712. (d) Kuriyama, M.; Hamaguchi, N.; Onomura, O. *Chem.—Eur. J.* **2012**, *18*, 1591−1594. (e) Lindstedt, E.; Ghosh, R.; Olofsson, B. *Org. Lett.* **2013**, *15*, 6070−6073. (f) Ghosh, R.; Olofsson, B. *Org. Lett.* **2014**, *16*, 1830−1832 For the arylation of C-center, see:. (g) Beringer, F. M.; Forgione, P. S.; Yudis, M. D. *Tetrahedron* **1960**, *8*, 49−63. (h) Beringer, F. M.; Daniel, W. J.; Galton, S. A.; Rubin, G. *J. Org. Chem.* **1966**, *31*, 4315−4318. (i) Chen, Z.; Jin, Y.; Stang, P. J. *J. Org. Chem.* **1987**, *52*, 4115−4117. (j) Beringer, F. M.; Galton, S. A. *J. Org. Chem.* **1963**, *28*, 3417−3421. (k) Ochiai, M.; Kitagawa, Y.; Toyonari, M. *ARKIVOC* **2003**, 43−48. (l) Oh, C. H.; Kim, J. S.; Jung, H. H. *J. Org. Chem.* **1999**, *64*, 1338−1340. (m) Grushin, V. V. *Acc. Chem. Res.* **1992**, *25*, 529−536. (n) Grushin, V. V.; Demkina, I. I.; Tolstaya, T. P. *J. Chem. Soc., Perkin Trans. 2* **1992**, 505−511. (o) Allen, A. E.; MacMillan, D. W. C. *J. Am. Chem. Soc.* **2011**, *133*, 4260−4263. (p) Harvey, J. S.; Simonovich, S. P.; Jamison, C. R.; MacMillan, D. W. C. *J. Am. Chem. Soc.* **2011**, *133*, 13782−13785. (q) Rousseaux, S.; Vrancken, E.; Campagne, J.-M. *Angew. Chem., Int. Ed.* **2012**, *51*, 10934−10935. (r) Bigot, A.; Williamson, A. E.; Gaunt, M. J. *J. Am. Chem. Soc.* **2011**, *133*, 13778−13781. (s) Norrby, P.-O.; Petersen, T. B.; Bielawski, M.; Olofsson, B. *Chem.—Eur. J.* **2010**, *16*, 8251−8254. (t) Ryana, J. H.; Stang, P. J. *Tetrahedron Lett.* **1997**, *38*, 5061−5064.

(8) (a) Phipps, R. J.; Grimster, N. P.; Gaunt, M. J. *J. Am. Chem. Soc.* **2008**, *130*, 8172−8173. (b) Deprez, N. R.; Kalyani, D.; Krause, A.; Sanford, M. S. *J. Am. Chem. Soc.* **2006**, *128*, 4972−4973. (c) Daugulis, O.; Zaitsev, V. G. *Angew. Chem., Int. Ed.* **2005**, *44*, 4046−4048. (d) Phipps, R. J.; Gaunt, M. J. *Science* **2009**, *323*, 1593−1597.

(9) Stewart, G. W.; Shevlin, M.; Yamagata, A. D. G.; Gibson, A. W.; Keen, S. P.; Scott, J. P. *Org. Lett.* **2012**, *14*, 5440−5443.

(10) Deprez, N. R.; Sanford, M. S. *Inorg. Chem.* **2007**, *46*, 1924−1935.

(11) (a) Kirsch, P. *Modern Fluoroorganic Chemistry*; Wiley-VCH: Weinheim, 2004. (b) Shimizu, M.; Hiyama, T. *Angew. Chem., Int. Ed.* **2005**, *44*, 214−231. (c) Muller, K.; Faeh, C.; Diederich, F. *Science* **2007**, *317*, 1881−1886. (d) Pacheco, M. C.; Purser, S.; Gouverneur, V. *Chem. Rev.* **2008**, *108*, 1943−1981. (e) Purser, S.; Moore, P. R.; Swallow, S.; Gouverneur, V. *Chem. Soc. Rev.* **2008**, *37*, 320−330.

(12) (a) Shimizu, M.; Takeda, Y.; Higashi, M.; Hiyama, T. *Angew. Chem., Int. Ed.* **2009**, *48*, 3653−3656. For recent examples of synthesis of trifluoromethyl alkenes, see: (b) Kobayashi, T.; Eda, T.; Tamura, O.; Ishibashi, H. *J. Org. Chem.* **2002**, *67*, 3156−3159. (c) Cho, E. J.; Buchwald, S. L. *Org. Lett.* **2011**, *13*, 6552−6555. (d) Parsons, A. T.; Senecal, T. D.; Buchwald, S. L. *Angew. Chem., Int. Ed.* **2012**, *51*, 2947−2950. (e) He, Z.; Luo, T.; Hu, M.; Cao, Y.; Hu, J. *Angew. Chem., Int. Ed.* **2012**, *51*, 3944−3947. (f) Xu, J.; Luo, D.; Xiao, B.; Liu, Z.; Gong, T.; Fu, Y.; Liu, L. *Chem. Commun.* **2011**, *47*, 4300−4302. (g) Liu, T.; Shen, Q. *Org. Lett.* **2011**, *13*, 2342. (h) Li, Z.; Cui, Z.; Liu, Z. *Org. Lett.* **2013**, *15*, 406−409.

(13) (a) Kharrat, S. E.; Laurent, P.; Blancou, H. *J. Org. Chem.* **2006**, *71*, 6742−6752. (b) Kharrat, S. E.; Kharrat, R. E.; Laurent, P.; Blancou, H. *Synthesis* **2007**, 3542−3552.

(14) (a) Huang, Z.; Hartwig, J. F. *Angew. Chem., Int. Ed.* **2012**, *51*, 1028−1032. (b) He, C.; Zhang, G. H.; Ke, J.; Zhang, H.; Miller, J. T.; Kropf, A. J.; Lei, A. W. *J. Am. Chem. Soc.* **2013**, *135*, 488−493.