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Rh^{III}-Catalyzed Olefination of 2-Aryloxypyridines Using 2-Pyridyloxyl as the Removable Directing Group

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An efficient Rh^{III}-catalyzed *trans* selective *ortho*-olefination of 2-aryloxypyridines has been developed. The catalytic system is very effective for olefination of differently substituted 2-aryloxypyridines with acrylates, acrylamide and styrenes and exhibits broad compatibility with assorted olefinic coupling partners. Although acrylates and acrylamide give rise to *trans*-olefinated products in MeOH, styrenes provided the *trans* products under solvent free reaction conditions. Interestingly, in olefinations with ethyl acrylate, the aryloxypyridine compound bearing keto functionality at the *ortho* position was found to undergo directing group cleavage to afford the olefinated phenol product directly.

Introduction

Transition metal-catalyzed direct C–H bond activation/functionalization has emerged as a powerful method for construction of carbon–carbon bonds characterized by economy of atoms and number of steps as well as features of green chemistry.[1] Consequently, valuable polyfunctional compounds can be synthesized expediently by this strategy. Among these transformations, cross-dehydrogenative couplings have emerged as increasingly powerful tools as they oxidatively couple two different C–H bonds.[2] Notable advances have been achieved in this area primarily through the use of Rh, Ru and Pd catalysts. The construction of C–C bonds, especially the coupling of arenes with olefins via a two-fold C–H activation process has drawn the attention of chemists in recent years.[2] To control the regioselectivity of the activation process, directing groups are usually introduced. However, this approach may sometimes be restricted in its effectiveness when the directing groups cannot be easily removed following the desired coupling. Hence, significant effort has been focused on developing removable directing groups.[3] Recently, a number of C–C bond forming reactions assisted by the 2-pyridyloxyl group have been developed.[3f,3j–3m,3t–3x] Phenol derivatives, in particular, have attracted significant attention in C–H bond functionalization processes due to their broad synthetic utility.[4] Among such derivatives, aryloxypyridine compounds exhibit important bioactivities and are thereby drawing much attention in the pharmaceutical field.[5] Hence, development of efficient routes for structural modification of such compounds is clearly warranted. The C–H activation of 2-aryloxypyridine has been realized due to formation of favored six-membered metallacyles.[6] Rh^{III} has played a crucial role in catalyst development for dehydrogenative *ortho* C–H olefination of arenes bearing a diverse set of Lewis-basic directing groups like anilides,[7] amides,[8] keto moieties,[8a] carbamates,[9] esters,[10] oximes,[11] carboxylic acids[12] sulfoxides,[13] pyrazoles[14] and others. However reports of Rh^{III}-catalyzed alkenylations of arenes that exploit removable directing groups remain scarce.[3i] Recently, Ackermann[3l] and Shi[3u] have reported olefinations of 2-phenoxypyridines using Ru^{II} and Pd^{II} catalysts, respectively. However, these methods are limited to acrylates as the olefinic coupling partners. In continuation of arene olefination development using 2-pyridyloxyl as the directing group, we have explored the efficacy of Rh catalysts and found a Rh^{III} catalyst that is very effective and compatible with a broad scope of olefins relative to earlier protocols. In the present investigation, apart from acrylates and acrylamide, we report our notable success using styrenes as the olefinic coupling partners.

Results and Discussion

At the outset, reaction conditions were optimized using 2-phenoxypyridine (**1a**) and ethyl acrylate (**2**) as the model substrates (Table 1). We initiated the coupling process using $[Cp^*RhCl_2]_2$ (5 mol-%) as the catalyst in the presence of 1 equiv. $Cu(OAc)_2{\cdot}H_2O$ as an oxidant and DCE as solvent (Table 1, Entry 1). The reaction was carried out at 110 °C. Only trace amounts of the desired coupled product formation were observed. However, we were pleased to get 33% of *ortho*-olefinated product **3a** in the presence of $AgSbF_6$ as an additive (Table 1, Entry 2). In this reaction we also recorded formation of trace di-olefinated product **3a′**. This result implied that in-situ generated cationic Rh^{III} complex

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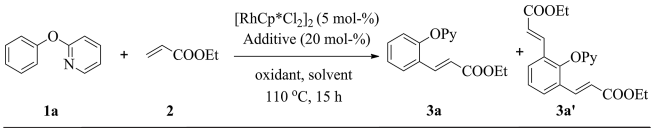
plays a vital role in the coupling process. The installed olefin was in the *E*-form almost exclusively. The cationic Rh^{III} species enabled the desired olefination with moderate yield in the presence of $Cu(OAc)_2 \cdot H_2O$ (51% **3a**, mono/di = 3.6:1, Table 1, Entry 3) revealing that the alkenylation process is effective under oxidative conditions. Next, we examined the efficiency of different oxidants in DCE towards the olefination process (Table 1, Entries 4–9). We were delighted to find that the yield of singly olefinated product improved to 65% with 1 equiv. of $Cu(OAc)_2$ (mono/di = 3.6:1, Table 1, Entry 8). Lowering the amount of $Cu(OAc)_2$ (0.5 equiv., Table 1, Entry 10) failed to change this efficiency. Thus, in the next step, we planned to achieve improved reaction selectivity (favoring mono-olefinated product) by varying the solvent while using 0.5 equiv. of $Cu(OAc)_2$. Among the different solvents used in trial reactions, MeOH (Table 1, Entry 13) was found to be ideal and the mono-olefinated product was isolated in 70% yield (mono/di = 5.4:1). On the basis of these data, we envisioned optimal reaction conditions to call for 0.5 equiv. $Cu(OAc)_2$ in MeOH at 110 °C. Lowering reaction temperature (Table 1, Entry 16) and catalyst loading (Table 1, Entry 17) provided comparatively lower yields. Additional experiments have shown that, in absence of catalyst, no reaction occurs (Table 1, Entry 18).

Table 1. Optimization of reaction conditions.[a]

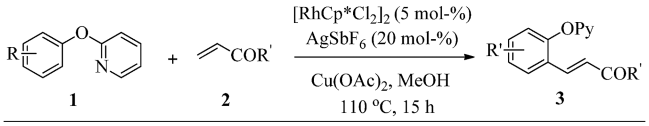


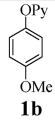
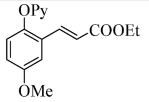
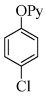
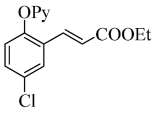
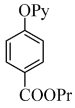
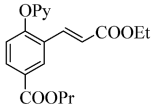
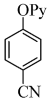
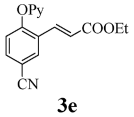
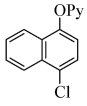
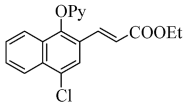
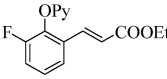
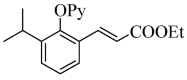
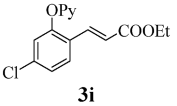
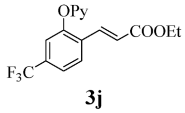
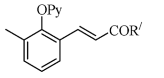
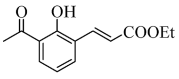
Entry	Additive	Oxidant (equiv.)	Solvent	Yields[b] [%] **3a**, **3a′**
1	–	$Cu(OAc)_2 \cdot H_2O$(1)	1,2-DCE	trace
2	$AgSbF_6$	–	1,2-DCE	33, trace
3	$AgSbF_6$	$Cu(OAc)_2 \cdot H_2O$(1)	1,2-DCE	51, 14
4	$AgSbF_6$	PhIOAc (1)	1,2-DCE	45, 10
5	$AgSbF_6$	AgOAc (1)	1,2-DCE	54, 12
6	$AgSbF_6$	Ag_2O(1)	1,2-DCE	60, 23
7	$AgSbF_6$	$K_2S_2O_8$ (1)	1,2-DCE	26, trace
8	$AgSbF_6$	$Cu(OAc)_2$(1)	1,2-DCE	65, 18
9	$AgSbF_6$	$Cu(OTf)_2$(1)	1,2-DCE	trace
10	$AgSbF_6$	$Cu(OAc)_2$(0.5)	1,2-DCE	64, 18
11	$AgSbF_6$	$Cu(OAc)_2$(0.5)	DMF	53, 14
12	$AgSbF_6$	$Cu(OAc)_2$(0.5)	*t*AmOH	44, 20
13	$AgSbF_6$	$Cu(OAc)_2$(0.5)	MeOH	70, 13
14	$AgSbF_6$	$Cu(OAc)_2$(0.5)	PhMe	52, 29
15	$AgSbF_6$	$Cu(OAc)_2$(0.5)	1,4-dioxane	n.r.
16[c]	$AgSbF_6$	$Cu(OAc)_2$(0.5)	MeOH	54, 16
17[d]	$AgSbF_6$	$Cu(OAc)_2$ (0.5)	MeOH	60, 12
18[e]	–	$Cu(OAc)_2$(0.5)	MeOH	n.r.

[a] Reaction condition:**1a** (0.2 mmol), ethyl acrylate (1.5 equiv.), $[RhCp^*Cl_2]_2$ (5 mol-%), $AgSbF_6$ (20 mol-%), solvent (2.5 mL), oxidant, 110 °C, 15 h. [b] Isolated yield. [c] Carried out at 90 °C. [d] $[RhCp^*Cl_2]_2$ (2.5 mol-%), $AgSbF_6$ (10 mol-%). [e] Without Rh catalyst; n.r.: no reaction.

With the optimized reaction conditions in hand, the scope of substrates was investigated by using differently substituted 2-aryloxypyridines (**1**) with ethyl acrylate as the standard coupling partner (Table 2). A wide range of different substitution patterns was found to be compatible to the optimized coupling conditions; corresponding *trans* ole-

Table 2. Scope of Rh^{III}-catalyzed olefination process with acrylates.[a]



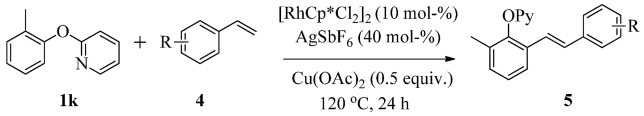
Entry	Substrate	Product	Yield (%)[b]
1	 **1b**	 **3b**	56 , 17[c]
2	 **1c**	 **3c**	54, 14[c]
3	 **1d**	 **3d**	52, 15[c]
4	 **1e**	 **3e**	32
5	 **1f**	 **3f**	65
6	 **1g**	 **3g**	71
7	 **1h**	 **3h**	77
8	 **1i**	 **3i**	74
9	 **1j**	 **3j**	71
10	 **1k**		**3k**, R' = OEt, 80 **3l**, R' = OMe, 78 **3m**, R' = OBu, 71 **3n**, R' = OBn, 68 **3o**, R' = $N(Me)_2$, 67 **3p**, R' = OH, n.d.[d]
11	 **1l**	 **3q**	66

[a] Reaction condition: **1** (0.2 mmol), **2** (1.5 equiv.), $[RhCp^*Cl_2]_2$ (5 mol-%), $AgSbF_6$ (20 mol-%), MeOH (2.5 mL), $Cu(OAc)_2$ (0.5 equiv.), 110 °C, 15 h. [b] Isolated yield. [c] Di-olefinated product. [d] Formation of the olefinated product was not detected.

finated products were routinely obtained in moderate to high yields. Electrophilic functional groups like halogens, esters, ketones and trifluoromethyl groups were found to be very well tolerated. However the cyano functionality (**1e**) correlated to reduced yield; only 32% mono-olefinated product was obtained in this case. In case of unsubstituted (**1a**) and *para*-substituted phenol derivatives (**1b**–**e**), the selectivity for mono-olefination was not well-controlled and di-olefinated products were also obtained to a lesser extent. For *ortho*-substituted phenol derivatives (**1f**–**h**, **1k**–**l**), the olefinated products were isolated in very good yields (65–80%). Interestingly, the compound bearing the keto functionality at the *ortho* position (**1l**) was found to undergo cleavage of the directing group under the reaction conditions and provided the olefinated phenol directly with a 66% yield (**3q**). The olefinated product bearing the directing group was not detected in this reaction and, at present, it is not clear why the directing group is so readily cleaved in this case. For *meta*-substituted phenol derivatives (**1i**–**j**), olefination proceeded regioselectively at the sterically less hindered *ortho* position providing only mono-olefinated products. The present protocol was successfully extended to other acrylates like methyl, butyl and benzyl acrylates and provided the corresponding olefinated products (**3l–n**) in high yields. We also investigated the versatility of the catalytic system with *N*,*N*-dimethyacrylamide and acrylic acid. Although the acrylamide, under the reaction conditions, provided olefinated product in good yield (**3o**, 67%), the use of acrylic acid failed to provide desired product **3p**.

Relative to acrylates, styrenes are less active and hence, challenging coupling partners when it comes to alkenylation reactions. We were very pleased to find that the Rh^{III}-catalyst is very effective for olefination of styrene compounds. Using the *ortho*-methyl-substituted phenol derivative, **1k** and styrene as the model coupling partner, we isolated just 20% of the olefinated product under the standard reaction conditions developed for acrylates. In attempts to improve coupling yields we employed solvent free conditions calling for 10 mol-% catalyst at 120 °C and found these to be optimal for the given coupling partners. Under these conditions, the use of 0.2 mL of styrene afforded product **5a** in 80% yield and exclusively in the *trans*-form. Inspired by this suc-

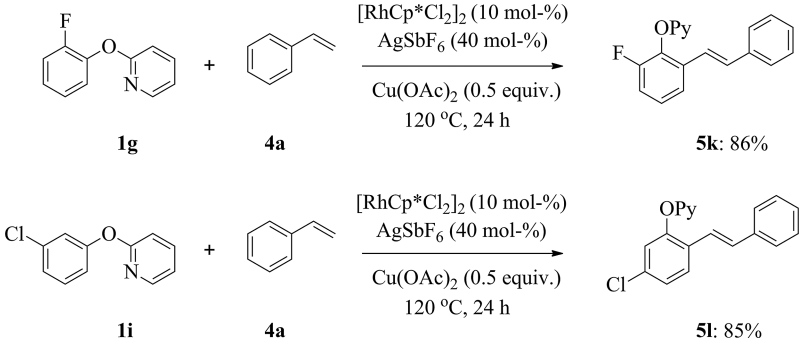
Table 3. Scope of Rh^{III}-catalyzed olefination with styrenes.[a]



1k 4 5

Entry	Styrenes	Product	Yield (%)[b]
1	**4a**	**5a**	84
2	**4b**	**5b**	78
3	**4c**	**5c**	58
4	**4d**	**5d**	82
5	**4e**	**5e**	55
6	**4f**	**5f**	60
7	**4g**	**5g**	76
8	**4h**	**5h**	77
9	4i	**5i**	91
10	**4j**	**5j**	70

[a] Reaction condition: **1k** (0.2 mmol), **4** (0.2 mL), $[RhCp^*Cl_2]_2$ (10 mol-%), $AgSbF_6$ (40 mol-%), $Cu(OAc)_2$ (0.5 equiv.), 120 °C, 24 h. [b] Isolated yield.



Scheme 1.

cess, we extended our reaction to different liquid styrenes and successfully isolated the corresponding *trans*-olefinated products in moderate to excellent yield (**5b**–**j**, up to 91%). Different styrene substituents were found to be very well tolerated. Importantly however, the present protocol is limited to liquid styrenes (Table 3).

The styrene-based olefination conditions were also successfully extended to other 2-aryloxypyridines (Scheme 1) and anticipated products were isolated in excellent yields. The *meta*-substituted phenol derivative (**1i**) provided mono-olefinated product (**5l**) regioselectively at the sterically less hindered *ortho* position. The *trans* configuration of olefinated products were unambiguously determined by X-ray crystallography analysis using **5l** as the representative example (Figure 1).

The 2-pyridyl group can be removed using standardized procedures.[3l,3u] Using the previously reported protocol we have successfully cleaved the directing group from compound **5a** (Scheme 2) to deliver free phenol **5m** (91%).

On the basis of literature, a plausible mechanistic pathway has been proposed (Scheme 3) for the olefination described herein.[10a,15] $[RhCp^*Cl_2]_2$ dissociates initially into an unsaturated monomeric species, which reacts with $AgSbF_6$ generating cationic Rh^{III} species **A**. Electrophilic species **A** is expected to readily coordinate the pyridine *N*-atom of the substrate forming intermediate **B**. Subsequently, a concerted metalation–deprotonation process at the *ortho* position is envisioned to afford arylrhodium species **C**. Olefin insertion into the carbon–Rh^{III} bond generates rhodacycle **D**, from which β-hydride elimination pro-

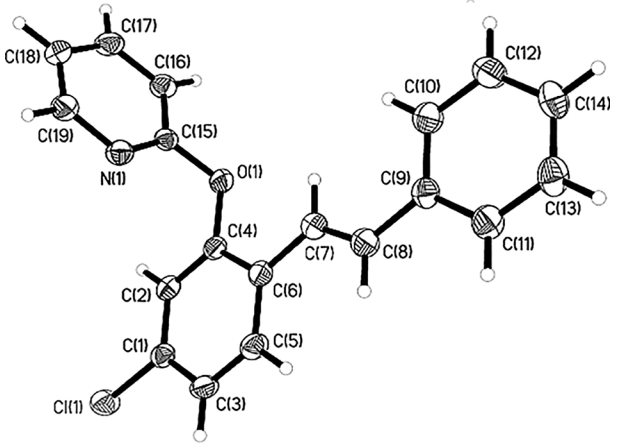
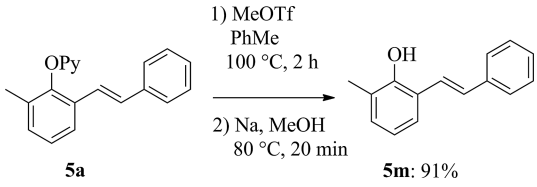
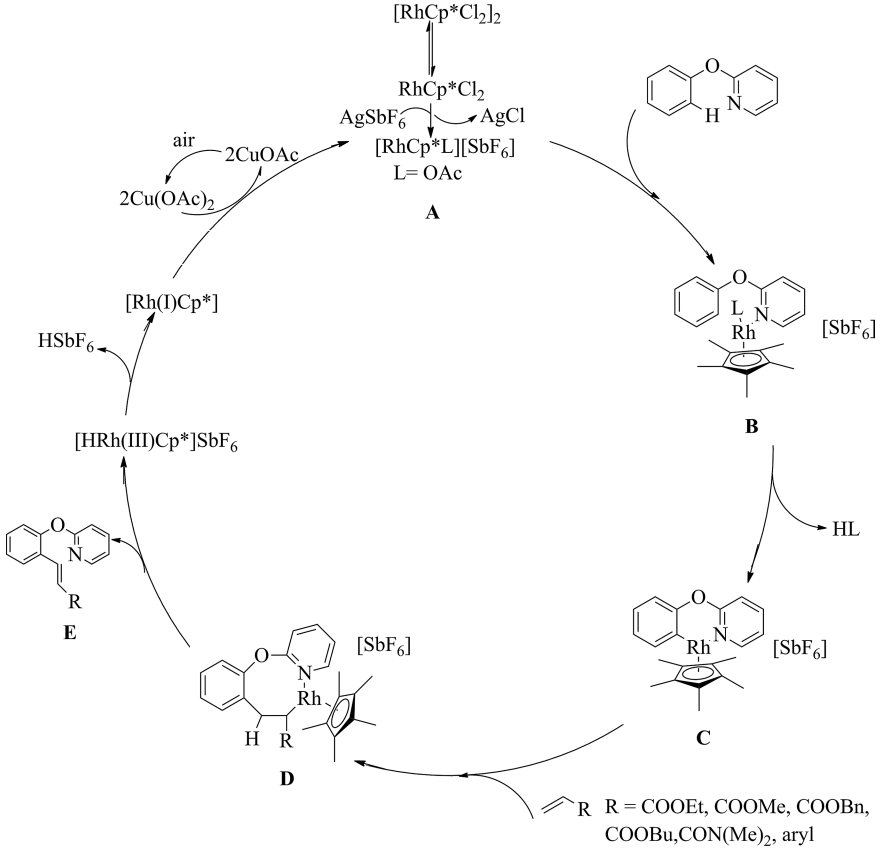


Figure 1. ORTEP drawing of compound **5l**.



Scheme 2. Removal of 2-pyridyl-based directing group from model compound **5a**.



Scheme 3. Proposed mechanism for Rh^{III}-catalyzed olefination.

vides the olefinated product **E** along with the $[HRh^{III}Cp^*]SbF_6$ species. Reductive elimination of $[HRh^{III}Cp^*]SbF_6$ species gives a Rh^I species, which is reoxidized to Rh^{III} by the action of $Cu(OAc)_2$. Finally, the transiently reduced copper is then air oxidized.

Conclusions

In sum, we have developed a simple and efficient Rh^{III}-catalyzed direct C–H olefination of arenes displaying a removable directing group. The scope of the olefination process is broad; differently substituted 2-aryloxypyridines effectively provide *trans*-olefinated products by virtue of their coupling with acrylates, acrylamide and styrenes. The products were isolated in moderate to excellent yields. Acrylates and acrylamide provide the desired olefinated products when using MeOH as the optimized solvent. Comparatively, at a higher loading of catalyst under solvent free conditions, styrenes provide the desired olefinated products in excellent yields. Interestingly, during olefination with ethyl acrylate, the aryloxypyridine compound bearing a keto functionality at the *ortho* position was found to undergo cleavage of the directing group and directly provided the olefinated phenol. Products can be readily liberated from the directing group using a previously reported protocol.

Experimental Section

General Procedure for the Olefination of 2-Aryloxypyridine (1) with Acrylates 3a–q: A mixture of $[RhCp^*Cl_2]_2$ (5 mol-%), $AgSbF_6$ (20 mol-%) and substrate **1**, (0.2 mmol) in MeOH (2.5 mL) was placed in a Schlenk tube and then combined with ethyl acrylate (1.5 equiv.) and $Cu(OAc)_2$ (0.5 equiv., mmol). The reaction mixture was allowed to stir for 15 h in a preheated oil bath at 110 °C. Reaction progress was monitored by thin layer chromatography. The reaction mixture was then cooled and passed through a short pad of Celite and washed with EtOAc. Organic solvents were removed under reduced pressure and the residue was purified by flash chromatography using PE and EtOAc (4.5:1) as eluent.

General Procedure for the Olefination of 1k with Styrenes 5a–j: A mixture of $[RhCp^*Cl_2]_2$ (10 mol-%), $AgSbF_6$ (40 mol-%), substrate **1k** (0.2 mmol) and styrene compound **4** (0.2 mL) was placed in a Schlenk tube and then combined with $Cu(OAc)_2$ (0.5 equiv.). The reaction mixture was allowed to stir for 24 h in a preheated oil bath at 120 °C. The reaction mixture was then cooled and added to EtOAc. The reaction mixture was passed through a short pad of Celite and washed with EtOAc. Organic solvents were removed under reduced pressure and the residue was purified by flash chromatography using PE and EtOAc (5:0.2) as eluent. Products **5k** and **5l** were also prepared and isolated in similar fashion.

CCDC-1405844 (for **5l**) contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

Supporting Information (see footnote on the first page of this article): Experimental procedures and characterization of all compounds including crystallographic data for compound **5l**.

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[1] Selected reviews: a) V. Ritleng, C. Sirlin, M. Pfeffer, *Chem. Rev.* **2002**, *102*, 1731–1770; b) O. Daugulis, H.-Q. Do, D. Shabashov, *Acc. Chem. Res.* **2009**, *42*, 1074–1086; c) A. A. Kulkarni, O. Daugulis, *Synthesis* **2009**, 4087–4109; d) X. Chen, K. M. Engle, D. H. Wang, J. Q. Yu, *Angew. Chem. Int. Ed.* **2009**, *48*, 5094–5115; *Angew. Chem.* **2009**, *121*, 5196; e) D. A. Colby, R. G. Bergman, J. A. Ellman, *Chem. Rev.* **2010**, *110*, 624–655; f) T. W. Lyons, M. S. Sanford, *Chem. Rev.* **2010**, *110*, 1147–1169; g) T. Satoh, M. Miura, *Chem. Eur. J.* **2010**, *16*, 11212–11222; h) C. L. Sun, B. J. Li, Z. J. Shi, *Chem. Rev.* **2011**, *111*, 1293–1314; i) L. Ackermann, *Chem. Rev.* **2011**, *111*, 1315–1345; j) J. Wencel-Delord, T. Dröge, F. Liu, F. Glorius, *Chem. Soc. Rev.* **2011**, *40*, 4740–4761; k) G. Song, F. Wang, X. Li, *Chem. Soc. Rev.* **2012**, *41*, 3651–3678; l) K. M. Engle, T.-S. Mei, M. Wasa, J.-Q. Yu, *Acc. Chem. Res.* **2012**, *45*, 788–802; m) P. B. Arockiam, C. Bruneau, P. H. Dixneuf, *Chem. Rev.* **2012**, *112*, 5879–5918.

[2] For selected reviews on cross-dehydrogenative C–H bond functionalizations, see: a) C.-J. Li, *Acc. Chem. Res.* **2009**, *42*, 335–344; b) C. J. Scheuermann, *Chem. Asian J.* **2010**, *5*, 436–451; c) C. S. Yeung, V. M. Dong, *Chem. Rev.* **2011**, *111*, 1215–1292; d) J. Le Bras, J. Muzart, *Chem. Rev.* **2011**, *111*, 1170–1214; e) F. W. Patureau, J. Wencel-Delord, F. Glorius, *Aldrichim. Acta* **2012**, *45*, 31–41; f) S. A. Girard, T. Knauber, C.-J. Li, *Angew. Chem. Int. Ed.* **2014**, *53*, 74–100; g) S. I. Kozhushkov, L. Ackermann, *Chem. Sci.* **2013**, *4*, 886–896; h) Y. N. Wu, J. Wang, F. Mao, F. Y. Kwong, *Chem. Asian J.* **2014**, *9*, 26–47.

[3] For recent reviews on the use of removable directing groups, see: a) C. Wang, Y. Huang, *Synlett* **2013**, *24*, 145–149; b) G. Rousseau, B. Breit, *Angew. Chem. Int. Ed.* **2011**, *50*, 2450–2494; *Angew. Chem.* **2011**, *123*, 2498. For illustrative examples of removable directing groups: c) A. García-Rubia, R. G. Arrayás, J. C. Carretero, *Angew. Chem. Int. Ed.* **2009**, *48*, 6511–6515; *Angew. Chem.* **2009**, *121*, 6633; d) N. Chernyak, A. S. Dudnik, C. Huang, V. Gevorgyan, *J. Am. Chem. Soc.* **2010**, *132*, 8270–8272; e) D. Shabashov, O. Daugulis, *J. Am. Chem. Soc.* **2010**, *132*, 3965–3972; f) J. H. Chu, P. S. Lin, M. J. Wu, *Organometallics* **2010**, *29*, 4058–4065; g) C.-H. Huang, B. Chattopadhyay, V. Gevorgyan, *J. Am. Chem. Soc.* **2011**, *133*, 12406–12409; h) M. Yu, Z. Liang, Y. Wang, Y. Zhang, *J. Org. Chem.* **2011**, *76*, 4987–4994; i) C. Wang, H. Chen, Z. Wang, J. Chen, Y. Huang, *Angew. Chem. Int. Ed.* **2012**, *51*, 7242–7245; *Angew. Chem.* **2012**, *124*, 7354; j) S. Guin, S. K. Rout, A. Banerjee, S. Nandi, B. K. Patel, *Org. Lett.* **2012**, *14*, 5294–5297; k) L. Ackermann, E. Diers, A. Manvar, *Org. Lett.* **2012**, *14*, 1154–1157; l) W. B. Ma, L. Ackermann, *Chem. Eur. J.* **2013**, *19*, 13925–13928; m) M. Kim, S. Sharma, J. Park, M. Kim, Y. Choi, Y. Jeon, J. H. Kwak, I. S. Kim, *Tetrahedron* **2013**, *69*, 6552–6559; n) L.-Q. Zhang, S. Yang, X. Huang, J. You, F. Song, *Chem. Commun.* **2013**, *49*, 8830–8832; o) F.-J. Chen, S. Zhao, F. Hu, K. Chen, Q. Zhang, S.-Q. Zhang, B.-F. Shi, *Chem. Sci.* **2013**, *4*, 4187–4192; p) K. Chen, F. Hu, S.-Q. Zhang, B.-F. Shi, *Chem. Sci.* **2013**, *4*, 3906–3911; q) B. Urones, R. G. Arrayás, J. C. Carretero, *Org. Lett.* **2013**, *15*, 1120–1123; r) X. Cong, J. You, J. Lan, *Chem. Commun.* **2013**, *49*, 662–664; s) J. Yao, R. Feng, Z. Wu, Z. Liu, Y. Zhang, *Adv. Synth. Catal.* **2013**, *355*, 1517–1522; t) B. Liu, H. Z. Jiang, B. F. Shi, *Org. Biomol. Chem.* **2014**, *12*, 2538–2542; u) B. Liu, H.-Z. Jiang, B.-F. Shi, *J. Org. Chem.* **2014**, *79*, 1521–1526; v) C. Zhang, P. Sun, *J. Org. Chem.* **2014**, *79*, 8457–8461; w) W. Zhang, J. Zhang, S. Ren, Y. Liu, *J. Org. Chem.* **2014**, *79*, 11508–11516; x) Y. Xu, P. Liu, S.-L. Li, P. Sun, *J. Org. Chem.* DOI: 10.1021/jo5026095.

[4] For selected references, see: a) T. A. Boebel, J. F. Hartwig, *J. Am. Chem. Soc.* **2008**, *130*, 7534–7535; b) S. Gu, C. Chen, W.

Chen, *J. Org. Chem.* **2009**, *74*, 7203–7206; c) X. Zhao, C. S. Yeung, V. M. Dong, *J. Am. Chem. Soc.* **2010**, *132*, 5837–5844; d) B. Xiao, Y. Fu, J. Xu, T.-J. Gong, J.-J. Dai, J. Yi, L. Liu, *J. Am. Chem. Soc.* **2010**, *132*, 468–469; e) B. Xiao, T.-J. Gong, Z.-J. Liu, J.-H. Liu, D.-F. Luo, J. Xu, L. Liu, *J. Am. Chem. Soc.* **2011**, *133*, 9250–9253; f) L. Niu, H. Yang, R. Wang, H. Fu, *Org. Lett.* **2012**, *14*, 2618–2621; g) H.-X. Dai, G. Li, X.-G. Zhang, A. F. Stepan, J.-Q. Yu, *J. Am. Chem. Soc.* **2013**, *135*, 7567–7571; h) B. Li, J. Ma, Y. Liang, N. Wang, S. Xu, H. Song, B. Wang, *Eur. J. Org. Chem.* **2013**, 1950–1962; i) W. Liu, L. Ackermann, *Org. Lett.* **2013**, *15*, 3484; j) C. Zhang, J. Ji, P. Sun, *J. Org. Chem.* **2014**, *79*, 3200–3205.

[5] a) F. Julémont, X. de Leval, C. Michaux, J.-F. Renard, J.-Y. Winum, J.-L. Montero, J. Damas, J.-M. Dogné, B. Pirotte, *J. Med. Chem.* **2004**, *47*, 6749–6759; b) C. W. am Ende, S. E. Knudson, N. Liu, J. Childs, T. J. Sullivan, M. Boyne, H. Xu, Y. Gegina, D. L. Knudson, F. Johnson, C. A. Peloquin, R. A. Slayden, P. J. Tonge, *Bioorg. Med. Chem. Lett.* **2008**, *18*, 3029–3033; c) M. A. Letavic, L. Aluisio, J. R. Atack, P. Bonaventure, N. I. Carruthers, C. Dugovic, A. Everson, M. A. Feinstein, I. C. Fraser, K. Hoey, X. Jiang, J. M. Keith, T. Koudriakova, P. Leung, B. Lord, T. W. Lovenberg, K. S. Ly, K. L. Morton, S. T. Motley, D. Nepomuceno, M. Rizzolio, R. Rynberg, K. Sepassi, J. Shelton, *Bioorg. Med. Chem. Lett.* **2010**, *20*, 4210–4214; d) X. Y. Song, W. M. Chen, L. Lin, C. H. Ruiz, M. D. Cameron, D. R. Duckett, T. M. Kamenecka, *Bioorg. Med. Chem. Lett.* **2011**, *21*, 7072–7075; e) H. Chao, H. Turdi, T. F. Herpin, J. Y. Roberge, Y. Liu, D. M. Schnur, M. A. Poss, R. Rehfuss, J. Hua, Q. Wu, L. A. Price, L. M. Abell, W. A. Schumacher, J. S. Bostwick, T. E. Steinbacher, A. B. Stewart, M. L. Ogletree, C. S. Huang, M. Chang, A. M. Cacace, M. J. Arcuri, D. Celani, R. R. Wexler, R. M. Lawrence, *J. Med. Chem.* **2013**, *56*, 1704–1714.

[6] a) D. J. de Geest, B. J. O'Keefe, P. J. Steel, *J. Organomet. Chem.* **1999**, *579*, 97–105; b) B. J. O'Keefe, P. J. Steel, *Organometallics* **2003**, *22*, 1281–1292.

[7] F. W. Patureau, F. Glorius, *J. Am. Chem. Soc.* **2010**, *132*, 9982–9983.

[8] a) F. W. Patureau, T. Besset, F. Glorius, *Angew. Chem. Int. Ed.* **2011**, *50*, 1064–1067; *Angew. Chem.* **2011**, *123*, 1096; b) S. Rakshit, C. Grohmann, T. Besset, F. Glorius, *J. Am. Chem. Soc.* **2011**, *133*, 2350–2353.

[9] a) T.-J. Gong, B. Xiao, Z.-J. Liu, J. Wan, J. Xu, D.-F. Luo, Y. Fu, L. Liu, *Org. Lett.* **2011**, *13*, 3235–3237; b) C. Feng, T.-P. Loh, *Chem. Commun.* **2011**, *47*, 10458–10460.

[10] a) S. H. Park, J. Y. Kim, S. Chang, *Org. Lett.* **2011**, *13*, 2372–2375; b) B. C. Chary, S. Kim, *Org. Biomol. Chem.* **2013**, *11*, 6879–6882.

[11] A. S. Tsai, M. Brasse, R. G. Bergman, J. A. Ellman, *Org. Lett.* **2011**, *13*, 540–542.

[12] a) K. Ueura, T. Satoh, M. Miura, *Org. Lett.* **2007**, *9*, 1407–1409; b) S. Mochida, K. Hirano, T. Satoh, M. Miura, *Org. Lett.* **2010**, *12*, 5776–5779; c) S. Mochida, K. Hirano, T. Satoh, M. Miura, *J. Org. Chem.* **2011**, *76*, 3024–3033.

[13] K. Nobushige, K. Hirano, T. Satoh, M. Miura, *Org. Lett.* **2014**, *16*, 1188–1191.

[14] N. Umeda, K. Hirano, T. Satoh, M. Miura, *J. Org. Chem.* **2009**, *74*, 7094–7099.

[15] a) Y. Boutadla, O. Al-Duaij, D. L. Davies, G. A. Griffith, K. Singh, *Organometallics* **2009**, *28*, 433–440; b) D. R. Stuart, P. Alsabeh, M. Kuhn, K. Fagnou, *J. Am. Chem. Soc.* **2010**, *132*, 18326–18339; c) N.-J. Wang, S.-T. Mei, L. Shuai, Y. Yuan, Y. Wei, *Org. Lett.* **2014**, *16*, 3040–3043.

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