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Regioselective aerobic oxidative Heck reactions with electronically unbiased alkenes: efficient access to α -alkyl vinylarenes†

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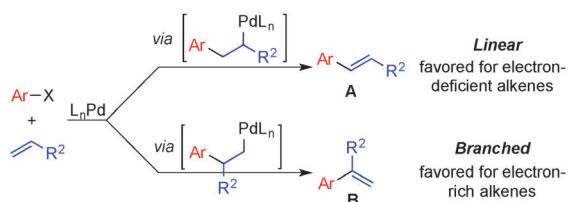
Branched-selective oxidative Heck coupling reactions have been developed between arylboronic acids and electronically unbiased terminal alkenes. The reactions exhibit high catalyst-controlled regioselectivity favoring the less common branched isomer. The reactions employ a catalyst composed of Pd(TFA)₂/dmphen (TFA = trifluoroacetate, dmphen = 2,9-dimethyl-1,10-phenanthroline) and proceed efficiently at 45–60 °C under 1 atm of O₂ without requiring other additives. A broad array of functional groups, including aryl halide, allyl silane and carboxylic acids are tolerated.

Mizoroki–Heck coupling reactions have found widespread use in organic synthesis¹ and are among the most versatile methods for selective functionalization of vinylic C–H bonds.² The ability to use unfunctionalized alkenes as substrates rather than vinyl halides represents a significant advantage over other cross-coupling methods for the synthesis of substituted alkenes. Several challenges, however, limit the scope of these reactions and prevent the advantages from being fully realized. Most precedents achieve regioselectivity by using substrates that have an intrinsic electronic bias (Scheme 1). Electron-deficient alkenes such as acrylates and styrenes favor coupling at the terminal position to give the linear products,³ while electron-rich vinyl ethers and vinyl amides favor coupling adjacent to the heteroatom to give the branched products.⁴

When electronically unbiased alkenes are used, the reaction often undergoes competitive reactions to afford different regioisomers with low selectivity, typically favoring the linear regioisomer. These issues were illustrated by Heck in 1974 in the reaction of bromobenzene with *n*-hexene, which under commonly used conditions afforded the linear phenylhexene as the major product, together with three other isomeric products.⁵

Recent developments have begun to address these limitations through the identification of appropriate substrate partners, reaction conditions and catalyst systems. For example, White^{6a,b} and co-workers achieved substrate-controlled linear-selective product formation with electronically unbiased alkenes *via* the use of chelating functional groups in the alkene substrate. Sigman^{6c,d} *et al.* identified appropriate catalyst systems that could achieve linear-selective coupling of simple alkenes with arylboronic acids or aryl diazonium salts.

Branched-selective Heck coupling typically requires electron-rich substrates, as noted above,^{4,7} but recent advances have led to catalysts capable of achieving branched selectivity with unbiased alkenes. Specifically, Zhou and co-workers reported Pd⁰-catalyzed Heck-coupling reactions between aliphatic olefins and aryl triflates using a bulky bisphosphine “dnfp” ligand [dnfp = 1,1'-bis[di-(1-naphthyl)phosphino]-ferrocene].⁸ Jamison and co-workers reported Ni-catalyzed Heck-type coupling reactions of aryl sulfonates and related substrates with terminal olefins that achieve high levels of branched selectivity.^{9,10} Finally, in connection with our interest in Pd-catalyzed aerobic oxidative coupling reactions,¹¹ we recently developed a method for oxidative Heck coupling of vinylboronic acids and electronically unbiased alkenes that afford branched-selective 1,3-disubstituted conjugated dienes.¹² Here, we describe aerobic oxidative Heck reactions between arylboronic acids and electronically unbiased alkenes that proceed with high catalyst-controlled selectivity for the branched isomer. The sterically encumbered 2,9-dimethyl-1,10-phenanthroline (dmphen) ligand is crucial to control of the regioselectivity (Scheme 2).¹³ The resulting α -alkyl vinylarenes are important precursors to chiral building blocks (*via* asymmetric hydrogenation and other transformations)¹⁴ and intermediates in the synthesis of bioactive natural products.¹⁵

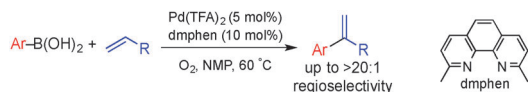


Scheme 1 Regioselectivity in Pd-catalyzed Heck coupling reactions.

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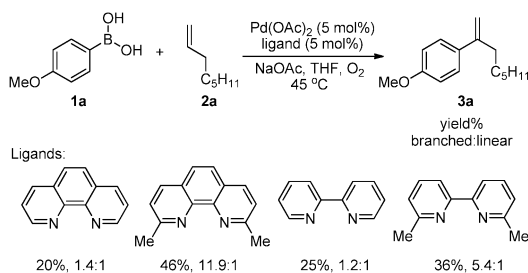
Scheme 2 Branched-selective aerobic oxidative Heck reactions with electronically unbiased alkenes.

The stability of α -branched styrenes relative to the conjugated dienes obtained in our previous study enables the reactions to proceed with improved efficiency. Furthermore, the mild air- and moisture-tolerant conditions allow the reactions to tolerate aryl halide and allyl silane substrates that are often not compatible with traditional cross-coupling conditions (including the branched-selective Heck reactions noted above).

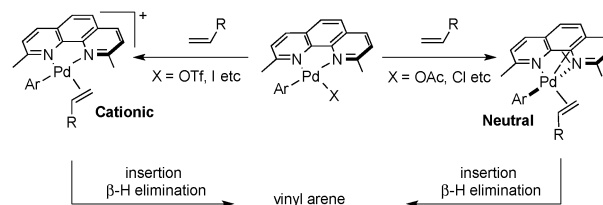
Our initial studies focused on assessing ligand effects on Pd(OAc)₂-catalyzed coupling of 4-methoxyphenylboronic acid (**1a**) and 1-octene (**2a**) in tetrahydrofuran (THF). Reactions with monodentate pyridine ligands such as pyridine and 2-fluoropyridine exhibited a slight preference for linear product formation, albeit with low yields (<10% yield). Improved results were obtained with bidentate nitrogen ligands (Scheme 3). Higher yields were observed with 2,9-dimethyl-1,10-phenanthroline (dmphen) and 6,6'-dimethyl-2,2'-bipyridine which bear two methyl groups adjacent to the two nitrogen atoms. The branched product was favored in both of these reactions, with branched:linear selectivity up to ~12:1 when the dmphen ligand was used. Related substituted-phen and -bpy ligands have been used previously in traditional and oxidative Heck-type coupling reactions; however, these precedents typically feature electronically biased substrates (e.g., vinyl amides or acrylates) in which the reactions exhibit product regioselectivity consistent with the substrate electronic effects.¹³

Cabri and co-workers have shown that Heck reactions that proceed *via* a “cationic pathway” exhibit enhanced selectivity for branched product formation with electron-rich alkenes owing to increased charge build-up in the alkene-insertion transition state.^{13b} The cationic pathway can be favored over a less regioselective five-coordinate neutral pathway by using less basic counterions and/or more polar solvent to facilitate dissociation of the anionic ligand (Scheme 4).

These considerations prompted us to test alternative counterions and solvents for the oxidative coupling of **1a** and **2a**. Selected results are summarized in Table 1. Up to 71% yield of the branched styrene product was obtained by replacing Pd(OAc)₂ with Pd(TFA)₂ and by changing the solvent from THF



Scheme 3 Preliminary ligand screening showing the influence of ligands on regioselectivity.



Scheme 4 Cationic versus neutral, five-coordinate pathways.

Table 1 Optimization of the oxidative Heck reaction^a

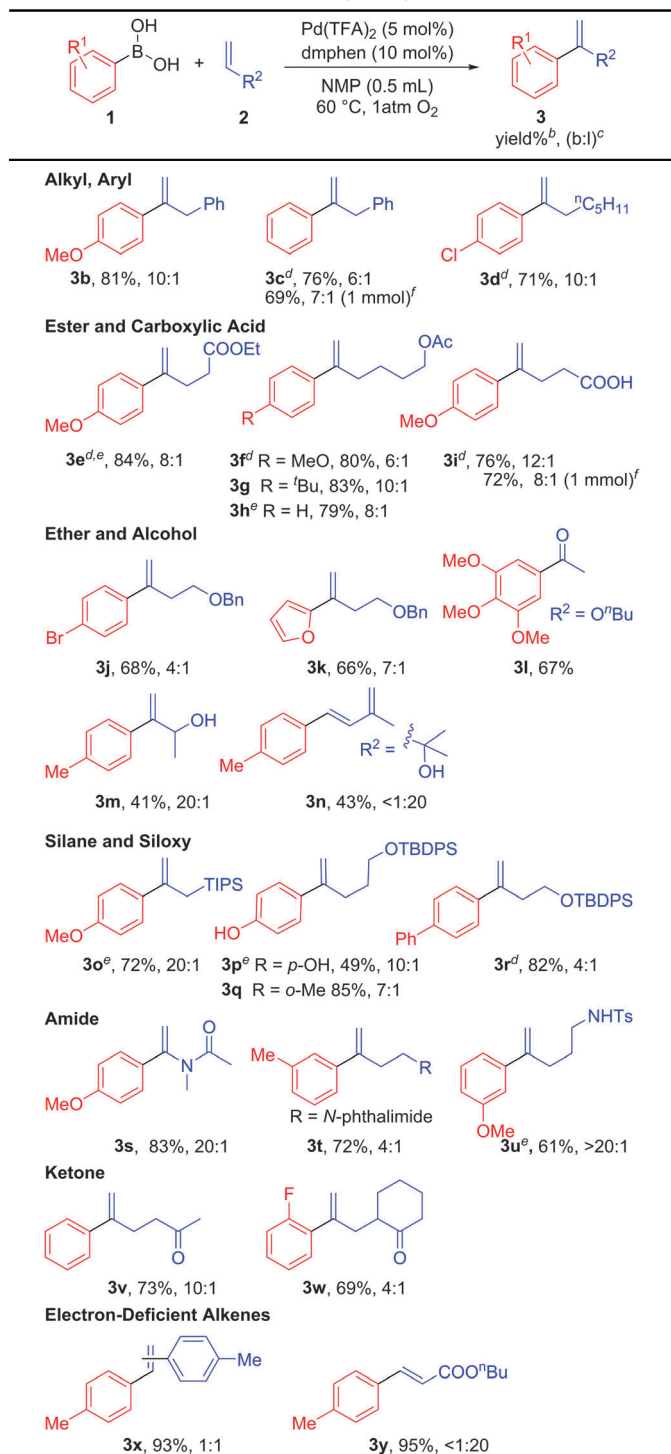
Entry	Pd/dmphen (x/y mol %)	Additive ^b	Solvent	Yield ^c (%)
1	5/10	—	Dioxane	55
2	5/10	—	CH ₃ CN	13
3	5/10	—	NMP	71
4	10/10	—	NMP	43
5	5/10	KF	NMP	57
6	5/10	PhCO ₂ H	NMP	62
7	5/10	NMM	NMP	60
8 ^d	5/10	—	NMP	60
9 ^e	5/10	—	NMP	72
10 ^{e,f}	5/10	—	NMP	75 (70)

^a Reaction conditions: **1a** (0.3 mmol), **2a** (0.2 mmol), NMP (0.5 mL), 6 h. ^b y mol% of the additives used. ^c GC yield based on **2a** (or limiting reagent). Regioselectivity (branched:linear) >15:1. ^d **1a/2a** = 0.2 mmol/0.2 mmol. ^e **1a/2a** = 0.2 mmol/0.4 mmol. ^f Reaction performed at 60 °C. NMM = *N*-methyl morpholine. NMP = *N*-methyl pyrrolidone.

to *N*-methylpyrrolidone (NMP) (*cf.* entry 3, Table 1). The best results were obtained by using a 2:1 dmphen: Pd ratio, possibly reflecting catalyst decomposition, which results in lower reaction yields at a 1:1 ligand: Pd ratio (*cf.* entry 4). All reactions with Pd(TFA)₂ as the Pd^{II} source exhibited high regioselectivity (>15:1), consistent with the involvement of the Cabri-like cationic pathway. The reactions performed in different solvents exhibited high regioselectivities in the presence of the Pd(TFA)₂/dmphen catalyst system (entries 1–3). Assessment of acidic and basic additives (e.g., entries 5–7) did not improve the reaction outcome. Standard reaction conditions employed 1.5 equiv. of the boronic acid to account for the small amount of homocoupling side reaction; however, good product yields were also obtained by using the arylboronic acid as the limiting reagent with excess alkene (2 equiv.) (72% yield; *cf.* entries 3 and 9). Increasing the reaction temperature to 60 °C led to a slight improvement in the yield (entry 10).

The additive-free reaction conditions identified above were then used to explore the substrate scope. Before performing tests with a broad substrate scope, several substrate partners were tested at different ratios between the arylboronic acid and alkene (1.5:1, 1:1, and 0.5:1). In general, the results at 1.5:1 substrate ratio afforded the best product yields, owing to the formation of small amounts of homocoupled biaryls from the boronic acid substrate (see Table S1 in the ESI† for details). The reactivities of a variety of arylboronic acids were tested with diverse alkenes, and the products are displayed in Table 2



Table 2 General scope with a variety of arylboronic acids and olefins^a

^a Reaction conditions: Pd(TFA)₂ (0.01 mmol), dmphen (0.02 mmol), NMP (0.5 mL), 60 °C, 6 h. For **3b**, **3e–3f**, **3o**: 1/2 = 0.2 mmol/0.4 mmol. For other substrates: 1/2 = 0.3 mmol/0.2 mmol. ^b Isolated yield. ^c Ratio of branched:linear was determined by ¹H NMR spectroscopy analysis of crude reaction mixture. ^d Isolated as a mixture of branched and linear (~10%) regioisomers. ^e Isomerization (~10%) to the internal alkenes occurred during purification. ^f Reaction in a round-bottom flask under O₂ balloon.

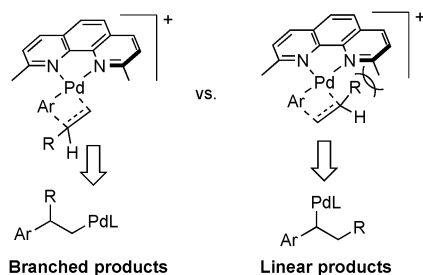
according to the different functional groups present in the alkene. Except where indicated otherwise, the reactions were performed with 1.5 equiv. of boronic acid relative to the alkene.

All of the yields were obtained following isolation and purification, and two of the products (**3c** and **3i**) were prepared on 1 mmol scale to confirm the reliability of the reactions.

The alkyl and phenyl containing alkenes reacted effectively with phenylboronic acids bearing *p*-MeO, -H, and -Cl substituents (**3a–3d**), with regioselectivity ranging from 6 : 1 (**3c**) to 15 : 1 (**3a**). Alkenes with ester moieties were even more effective, with yields typically above 80% (**3e–3g**). A free carboxylic acid was also well-tolerated in this reaction (**3i**). Three olefins with ether functionality, including *tert*-butyl vinyl ether, were demonstrated with electron deficient (*p*-bromophenyl) and electron-rich (2-furanyl, and 3,4,5-trimethoxyphenyl) boronic acids (**3j–3l**). It is worth noting that the bromide substituent derived from the arylboronic acid in **3j** (similar to the aryl chloride in **3d**) is tolerated owing to the mildness of the reaction conditions relative to typical Pd(0)-catalyzed reactions. The electron-rich *tert*-butyl vinyl ether substrate reacts exclusively with “branched” selectivity, as expected, and the resulting product then hydrolyzes *in situ* to give the aryl methyl ketone **3l**.¹⁶ Two alkenes with free alcohol groups proceed in modest yields (**3m** and **3n**). In the case of the tertiary alcohol 2-methyl-3-buten-2-ol, the product derives from linear-selective alkene functionalization, following by spontaneous dehydration to afford the conjugated diene **3n**. The switch in regioselectivity probably arises primarily from a steric effect of the fully substituted carbon center adjacent to the alkene. In contrast, an allyl silane with the sterically hindered triisopropylsilyl substituent (TIPS) proceeds in good yield (72%, **3o**) and excellent regioselectivity (20:1). In this case, the electron-donating beta-silicon effect, which should promote branched selectivity, presumably overrides any steric effect favoring the linear insertion product. This reactivity is quite appealing in light of the synthetic utility of substituted allyl silanes. Good results were also obtained with alkenes bearing remote siloxy groups (**3p–3r**), although the presence of the free phenol in the boronic acid used to afford **3p** appears to attenuate the product yield. An electronically biased vinyl amide affords the branched product **3s** in very good yield and regioselectivity, as expected, and remote phthalimide and secondary sulfonamide substituents were well tolerated (**3t**, **3u**). Alkenes with pendant ketones (a methyl ketone and cyclohexanone) also were effective substrates (**3v**, **3w**), and did not appear to be complicated by Pd-enolate formation (*e.g.*, which could lead to dehydrogenation¹⁷). Styrene and butyl acrylate are electronically biased alkenes that typically favor linear product formation. The linear product remains strongly preferred with our catalyst system in the case of butyl acrylate (**3y**: 95% yield with > 20 : 1 regioselectivity), but styrene affords a 1 : 1 mixture of regioisomeric products (**3x**).

Factors that govern regioselectivity in Heck-type coupling reactions have been discussed extensively in the literature.^{2c,13b} Bidentate ligands lead to cationic [Pd^{II}(L₂)(aryl)(alkene)]⁺ intermediates that exhibit higher branched selectivity relative to neutral Pd^{II}(L)(X)(aryl)(alkene) intermediates formed with monodentate ligands. The cationic charge enhances charge build-up in the alkene-insertion transition state, thereby favoring the branched (Markovnikov) product. Access to the cationic intermediate noted in Scheme 4 is facilitated by use of the trifluoroacetate





Scheme 5 Transition state structures showing the steric contributions to branched vs. linear product formation.

anion, which may be readily displaced by an alkene.¹⁸ Electronic effects are not sufficient to explain the present results, however, because bidentate ligands lacking the methyl groups exhibit little selectivity for the branched product (*cf.* Scheme 3). Thus, the high regioselectivity is best rationalized by synergistic electronic and steric effects, whereby the methyl groups in the dmphen ligand sterically inhibit formation of the linear coupling product, as depicted in Scheme 5.

In this study, we have identified a readily accessible Pd^{II} catalyst system for aerobic oxidative coupling of arylboronic acids and electronically unbiased alkenes. The catalyst enables highly regioselective formation of α -substituted vinylarenes with substrates bearing diverse functional groups. The ease of operation and broad substrate scope make this method readily accessible and highly appealing for synthetic applications.

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Notes and references

- For reviews, see: (a) A. B. Dounay and L. E. Overman, *Chem. Rev.*, 2003, **103**, 2945; (b) M. Shibasaki, E. M. Vogl and T. Ohshima, *Adv. Synth. Catal.*, 2004, **346**, 1533; (c) K. C. Nicolaou, P. G. Bulger and D. Sarlah, *Angew. Chem., Int. Ed.*, 2005, **44**, 4442.
- For reviews, see: (a) R. F. Heck, *Acc. Chem. Res.*, 1979, **12**, 146; (b) W. Cabri and I. Candiani, *Acc. Chem. Res.*, 1995, **28**, 2; (c) P. Nilsson, K. Olofsson and M. Larhed, in *The Mizoroki-Heck Reaction*, ed. M. Oestreich, John Wiley & Sons, Chichester, 2009, pp. 133–162; (d) B. Karimi, H. Behzadnia, D. Elhamifar, P. F. Akhavan, F. K. Esfahani and A. Zamani, *Synthesis*, 2010, 1399.
- (a) Y. C. Jung, R. K. Mishra, C. H. Yoon and K. W. Jung, *Org. Lett.*, 2003, **5**, 2231; (b) M. M. S. Andappan, P. Nilsson and M. Larhed, *Chem. Commun.*, 2004, 218; (c) J. Lindh, P. Enquist, Å. Pilotti, P. Nilsson and M. Larhed, *J. Org. Chem.*, 2007, **72**, 7957; (d) J. Ruan, X. Li, O. Saidi and J. Xiao, *J. Am. Chem. Soc.*, 2008, **130**, 2424; (e) J. Ruan, J. A. Iggo, N. G. Berry and J. Xiao, *J. Am. Chem. Soc.*, 2010, **132**, 16689.
- See ref. 3d and e and the following: (a) P. Harrison and G. Meek, *Tetrahedron Lett.*, 2004, **45**, 9277; (b) M. M. S. Andappan, P. Nilsson, H. V. Schenck and M. Larhed, *J. Org. Chem.*, 2004, **69**, 5212; (c) J. Mo, L. Xu and J. Xiao, *J. Am. Chem. Soc.*, 2005, **127**, 751; (d) A. L. Hansen and T. Skrydstrup, *J. Org. Chem.*, 2005, **70**, 5997; (e) J. Mo and J. Xiao, *Angew. Chem., Int. Ed.*, 2006, **45**, 4152.
- H. A. Dieck and R. F. Heck, *J. Am. Chem. Soc.*, 1974, **96**, 1133.
- (a) J. H. Delcamp and M. C. White, *J. Am. Chem. Soc.*, 2006, **128**, 15076; (b) J. H. Delcamp, A. P. Brucks and M. C. White, *J. Am. Chem. Soc.*, 2008, **130**, 11270; (c) E. W. Werner and M. S. Sigman, *J. Am. Chem. Soc.*, 2010, **132**, 13981; (d) E. W. Werner and M. S. Sigman, *J. Am. Chem. Soc.*, 2011, **133**, 9692.
- For examples of branched-selective Heck coupling with minimally biased substrates, such as allyl and homoallyl alcohols, see: (a) K. Olofsson, M. Larhed and A. Hallberg, *J. Org. Chem.*, 1998, **63**, 5076; (b) J. Mo, L. Xu, J. Ruan, S. Liu and J. Xiao, *Chem. Commun.*, 2006, 3591.
- (a) L. N. Qin, X. F. Ren, Y. P. Lu, Y. X. Li and J. R. Zhou, *Angew. Chem., Int. Ed.*, 2012, **51**, 5915; (b) L. N. Qin, H. Hirao and J. R. Zhou, *Chem. Commun.*, 2013, **49**, 10236. For α -arylation of vinylarenes, see: (c) Y. J. Zou, L. N. Qin, X. F. Ren, Y. P. Lu, Y. X. Li and J. R. Zhou, *Chem. – Eur. J.*, 2013, **19**, 3504.
- S. Z. Tasker, A. C. Gutierrez and T. F. Jamison, *Angew. Chem., Int. Ed.*, 2014, **53**, 1858.
- For Ni-catalyzed branched-selective benzylation of alkenes, see: (a) R. Matsubara, A. C. Gutierrez and T. F. Jamison, *J. Am. Chem. Soc.*, 2011, **133**, 19020; (b) E. A. Standley and T. F. Jamison, *J. Am. Chem. Soc.*, 2013, **135**, 1585.
- (a) A. N. Campbell and S. S. Stahl, *Acc. Chem. Res.*, 2012, **45**, 851; (b) Y. Izawa, C. Zheng and S. S. Stahl, *Angew. Chem., Int. Ed.*, 2013, **52**, 3672; (c) D. Wang, Y. Izawa and S. S. Stahl, *J. Am. Chem. Soc.*, 2014, **136**, 9914.
- C. Zheng, D. Wang and S. S. Stahl, *J. Am. Chem. Soc.*, 2012, **134**, 16496.
- For leading previous applications of dmphen as a ligand in oxidative and non-oxidative Heck reactions, see ref. 3b, c, 4a and the following: (a) W. Cabri, I. Candiani, A. Bedeschi and R. Santi, *Synlett*, 1992, 871; (b) W. Cabri, I. Candiani and A. Bedeschi, *J. Org. Chem.*, 1993, **58**, 7421; (c) P. A. Enquist, P. Nilsson, P. Sjoeborg and M. Larhed, *J. Org. Chem.*, 2006, **71**, 8779; (d) P. A. Enquist, J. Lindh, P. Nilsson and M. Larhed, *Green Chem.*, 2006, **8**, 338; (e) K. S. Yoo, C. H. Yoon and K. W. Jung, *J. Am. Chem. Soc.*, 2006, **128**, 16384; (f) J. O'Neill, K. S. Yoo and K. W. Jung, *Tetrahedron Lett.*, 2008, **49**, 7307; (g) A. Nordqvist, C. Bjoerkelid, M. Andaloussi, A. M. Jansson, S. L. Mowbray, A. Karlen and M. Larhed, *J. Org. Chem.*, 2011, **76**, 8986.
- For selected examples, see: (a) R. Corberán, N. W. Mszar and A. H. Hoveyda, *Angew. Chem., Int. Ed.*, 2011, **50**, 7079; (b) R. Zhu and S. L. Buchwald, *Angew. Chem., Int. Ed.*, 2013, **52**, 12655; (c) X. Sun, L. Zhou, C.-J. Wang and X. Zhang, *Angew. Chem., Int. Ed.*, 2007, **46**, 2623; (d) J. Chen, B. Cheng, M. Cao and Z. Lu, *Angew. Chem., Int. Ed.*, 2015, **54**, 4661.
- For selected examples, see: (a) S. P. Cook, A. Polara and S. J. Danishefsky, *J. Am. Chem. Soc.*, 2006, **128**, 16440; (b) M. B. Johansen and M. A. Kerr, *Org. Lett.*, 2008, **10**, 3497; (c) T. Ozawa, M. Kanematsu, H. Yokoe, M. Yoshida and K. Shishido, *J. Org. Chem.*, 2012, **77**, 9240; (d) M. Wu and D. Ma, *Angew. Chem., Int. Ed.*, 2013, **52**, 9759.
- Similar reactivity has been observed previously, for examples, see ref. 3c and d, 4b and c and the following: (a) W. Cabri, I. Candiani, A. Bedeschi and R. Santi, *J. Org. Chem.*, 1990, **55**, 3654; (b) T. M. Gøgsig, J. Kleimark, S. O. N. Lill, S. Korsager, A. T. Lindhardt, P.-O. Norrby and T. Skrydstrup, *J. Am. Chem. Soc.*, 2012, **134**, 443.
- Y. Izawa, D. Pun and S. S. Stahl, *Science*, 2011, **333**, 209.
- The ability of trifluoroacetate to promote formation of a cationic intermediate relative to acetate as an anionic ligand was the subject of considerable focus in the following study: A. B. Weinstein and S. S. Stahl, *Angew. Chem., Int. Ed.*, 2012, **51**, 11505.

