



Cite this: *Chem. Commun.*, 2015, 51, 4406

Received 15th January 2015,
Accepted 5th February 2015

DOI: 10.1039/c5cc00410a

www.rsc.org/chemcomm

Palladium(II)-catalysed *ortho*-arylation of *N*-benzylpiperidines†

Peng Wen Tan, Maxwell Haughey and Darren J. Dixon*

Pd^{II}-catalysed *ortho*-arylation of benzylic heterocycles with arylboronic acid pinacol esters (Ar-BPin) via directed C–H bond activation to generate the desired biaryl products is reported. This methodology is efficient and applicable to a wide range of functionalised Ar-BPin and benzylic heterocycles, allowing the direct synthesis of important biaryl motifs in modest to good yield.

Cross-coupling reactions of aromatic compounds constitute one of the most versatile entries to compounds possessing a biaryl motif.¹ Such transformations are usually performed by traditional cross coupling reactions of organohalides or pseudo-halides with organometallic reagents.² However, prefunctionalisation of substrates to form specific organohalides for cross coupling can be difficult and this has accordingly led many research groups to develop more direct routes to biaryl scaffolds.³ Over the last decade, a variety of direct, chelation-assisted, C–H activation on arenes, mainly *via* [Pd],⁴ [Rh]⁵ and [Ru]⁶ catalysis, has been developed using a wide range of directing groups (DGs) such as amides, imines, oximes, ketones and other N-heterocycles. Expanding the scope of DGs to include simple amine derivatives that are commonly found in natural products and pharmaceutical compounds is highly desirable. In 2006, Daugulis and co-workers reported an *ortho* arylation of unsubstituted benzylamines directed by the free amine with iodobenzene under Pd catalysis.⁷ Meanwhile, Shi *et al.* demonstrated that *N,N*-di-alkyl amine is also an effective directing group for *ortho*-olefination⁸ and -carbonylation.⁹ More recently, Zhang and co-workers^{10a} developed a Pd-catalysed *ortho*-arylation of *N,N*-dimethylbenzylamines with iodobenzene (Fig. 1).¹⁰ Inspired by these findings we envisaged that saturated N-containing heterocycles could also serve as efficient DGs for C(sp²)-H arylation; this would expand the range of DGs in the field (Fig. 1) and the new chemistry could be applied directly to the construction of

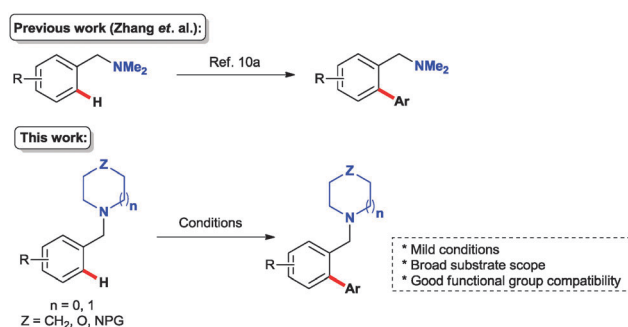


Fig. 1 *Ortho*-Arylation using benzylic heterocycles as directing groups.

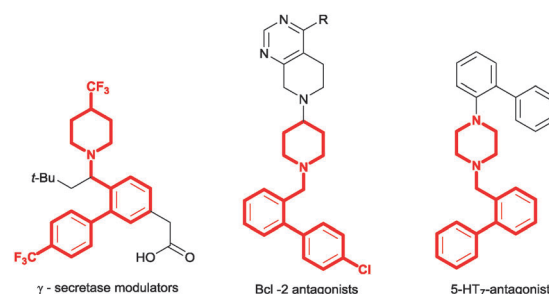


Fig. 2 Biologically active compounds containing a benzylpiperidine motif.

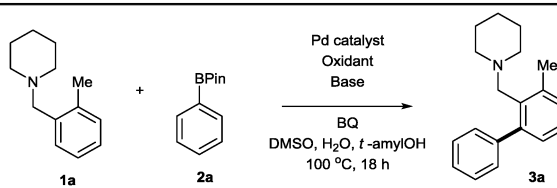
biologically relevant motifs such as those present, for example, in known Bcl-2 antagonists,¹¹ γ -secretase modulators¹² and 5-HT₇-antagonists¹³ (Fig. 2). Herein we report a Pd^{II}-catalysed *ortho*-arylation of a range of benzylic heterocycles with arylboronic acid pinacol esters leading directly to the biaryl product in one step.

Initially we focused on the piperidine moiety as a potentially useful directing group for C(sp²)-H activation/arylation. Inspired by Yu's pioneering work,¹⁴ a preliminary experiment was conducted on the model substrate 1-(2-methylbenzyl)piperidine **1a** and phenylboronic acid pinacol ester **2a** in the presence of catalytic Pd(OAc)₂, and Ag₂CO₃, Na₂CO₃ and 1,4-benzoquinone at 100 °C (Table 1). Encouragingly, *ortho*-arylated product **3a** was observed in 55% NMR yield (entry 1).

Department of Chemistry, Chemistry Research Laboratory, University of Oxford, 12 Mansfield Road, Oxford, OX1 3TA, UK. E-mail: darren.dixon@chem.ox.ac.uk

† Electronic supplementary information (ESI) available. See DOI: 10.1039/c5cc00410a



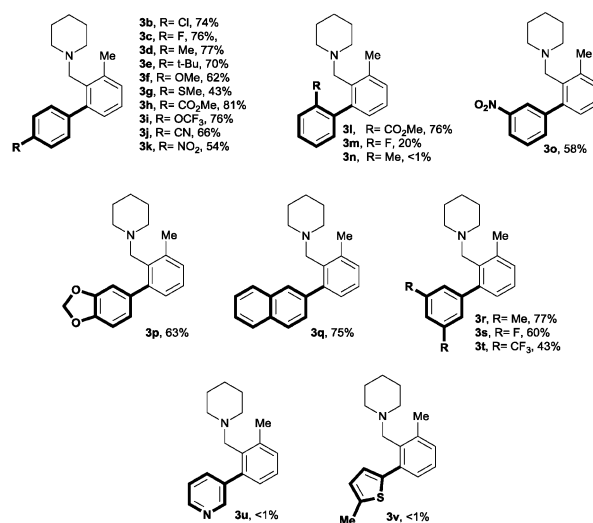
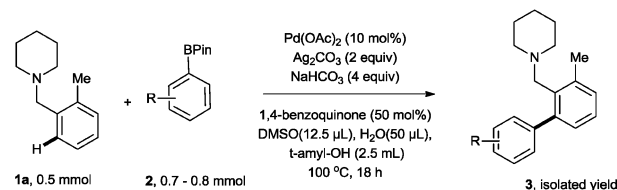
Table 1 Optimisation studies on C(sp²)-H activation/cross coupling reactions of **1a** & **2b**


Entry ^a	Catalyst (mol%)	Oxidant (equiv.)	Base (equiv.)	Yield ^c (%)
1	Pd(OAc) ₂ (10)	Ag ₂ CO ₃ (2.0)	Na ₂ CO ₃ (6.0)	55
2	Pd(OAc) ₂ (10)	Ag ₂ CO ₃ (2.0)	KF (6.0)	25
3	Pd(OAc) ₂ (10)	Ag ₂ CO ₃ (2.0)	K ₂ HPO ₄ (6.0)	33
4	Pd(OAc) ₂ (10)	Ag ₂ CO ₃ (1.5)	NaHCO ₃ (3.0)	82
5 ^b	PdCl ₂ (10)	Ag ₂ CO ₃ (1.5)	NaHCO ₃ (3.0)	—
6	Pd(OAc) ₂ (5)	Ag ₂ CO ₃ (1.5)	NaHCO ₃ (3.0)	43
7	Pd(OAc) ₂ (10)	Cu(OAc) ₂ (1.5)	NaHCO ₃ (3.0)	11
8	Pd(OAc) ₂ (10)	CuF ₂ (1.5)	NaHCO ₃ (3.0)	2
9	Pd(OAc)₂ (10)	Ag₂CO₃ (2.0)	NaHCO₃ (4.0)	88 (81)
10	Pd(OAc) ₂ (10)	AgOAc (2.0)	NaHCO ₃ (4.0)	81

^a Reaction condition: **1a** (0.2 mmol), **2b** (0.28 mmol), Pd catalyst, base, oxidant, BQ (0.5 equiv.), DMSO (5 μL), H₂O (20 μL) in *t*-amylOH (1 mL), *T* = 100 °C, 18 h. ^b Similar results for PdCl₂(PPh₃)₂ and PdCl₂(CH₃CN)₂. ^c ¹H NMR yield with internal standard (CH₂Br₂), in parenthesis isolated yield.

Further optimisation was then carried out, starting with an investigation of the performance of different bases. Potassium bases, KF and K₂HPO₄, resulted in a reduced yield (entries 2 & 3). Pleasingly, however, NaHCO₃ was found to be optimal for this transformation; full conversion of **1a** to the arylated product **3a** was observed after 18 hours (entry 4). Replacement of Pd(OAc)₂ with other Pd sources such as PdCl₂, PdCl₂(PPh₃)₂ and PdCl₂(CH₃CN)₂ did not result in the formation of any arylated product (entry 5). Decreasing the catalyst loading to 5 mol% resulted in a decrease in yield and therefore, 10 mol% of catalyst was deemed necessary (entry 6). Other oxidants such as Cu(OAc)₂ and CuF₂, were found to give inferior yields (entries 7 & 8) and although AgOAc was found to perform reasonably well (entry 10), Ag₂CO₃ proved optimal (entry 9). 1,4-Benzoquinone was also essential as a promoter; in its absence no reaction was observed in agreement with literature findings relating to its importance in the reductive elimination step.^{14b,15} A decline in yield was also observed without the addition of H₂O and DMSO (see the ESI[†]). *t*-Amyl alcohol was found to be the most suitable solvent for this transformation, followed by 1,4-dioxane and MeCN. Other aryl boronic acid derivatives were investigated, but arylboronic acid pinacol esters, were by far the best in this reaction (see the ESI[†]).

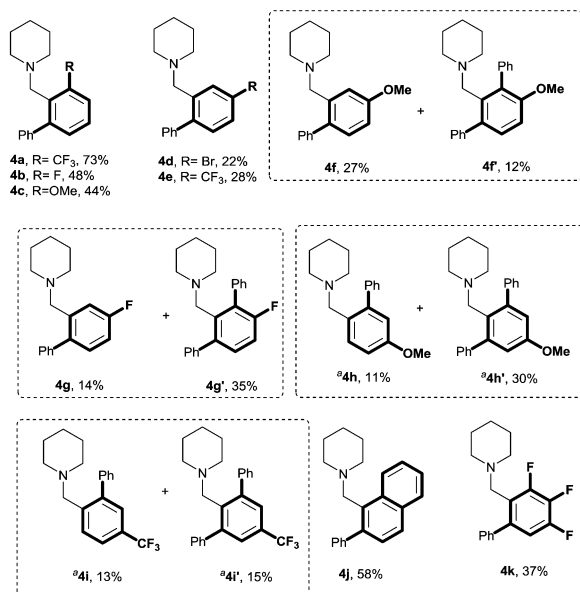
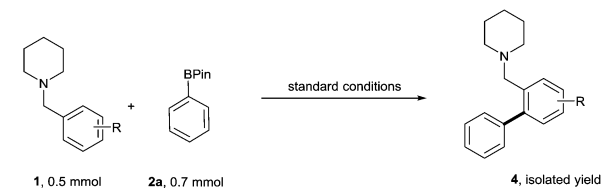
After attaining the optimised conditions, the scope of this methodology was assessed using different functionalized arylboronic acid pinacol esters (Ar-BPins) with 1-(2-methylbenzyl)piperidine (Scheme 1). Generally, a wide range of *para*-substituted Ar-BPin substrates was tolerated and the corresponding biaryl products were obtained in modest¹⁶ to good yields. Ar-BPins substituted with functional groups, such as cyano, nitro and fluorine were suitable substrates under these reaction conditions affording the desired products in respectable yields. Chlorine substituents on Ar-BPin were also well-tolerated, giving rise to biaryl products poised for further transformations. In the case of *ortho*-substituted Ar-BPin substrates, the reaction worked well using the ester **2l**

**Scheme 1** C(sp²)-H cross-coupling of 1-(2-methylbenzyl)piperidine with various Ar-BPin.

affording the biaryl product **3l** in a yield of 76% but, unfortunately, poor conversions were obtained for other substituents such as fluoro (**3m**) and methyl (**3n**). This methodology was also amenable to *meta*-substituted and 3,5-disubstituted Ar-Bpin derivatives, giving rise to the corresponding products in 43–77% yield. In agreement with related studies^{14f} heteroarylboronates that contained pyridine-(**3u**), thiophene-(**3v**) were unreactive under these conditions. Similarly, under the optimised conditions attempted *ortho* alkylation using cyclohexylboronic acid pinacol ester failed to yield any desired product.

The scope with respect to the substituents on the aromatic ring of the benzylpiperidine in the reaction with phenylboronic acid pinacol ester, was then examined. As presented in Scheme 2, *ortho*-substituted substrates possessing electron withdrawing (F and CF₃) and the electron donating (OMe) substituents performed well, with products being afforded in 44–73% yield. *meta* substituted substrates with sterically bulky electron withdrawing substituents (Br and CF₃) underwent monoarylation selectively at the less hindered *ortho* position, presumably due to steric effects, and afforded the products **4d** and **4e** in 22–28% yield. However, for less bulky electron withdrawing groups such as fluorine, products of both mono- and di-arylation, **4g** and **4g'**, were observed in 14% and 35% yield respectively. Notably, for an electron donating substituent at the *meta* position (OMe), in addition to affording the major monoarylated product **4f** (27%), diarylated product **4f'** was also isolated in 12% yield. The reaction conditions were also compatible with *para*-substituted substrates



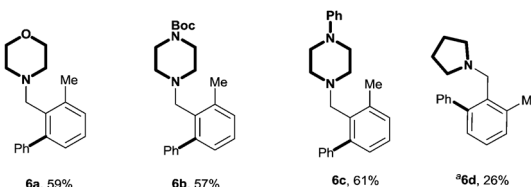
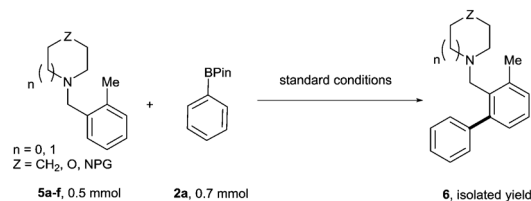


Scheme 2 C(sp²)-H cross-coupling of phenylboronic acid pinacol ester with different functionalised benzylpiperidines. ^a Reaction was carried out with **2a** (1.1 mmol) for 24 h.

affording a mixture of mono and di arylated products. Electron donating substituents (OMe) at the *para* position increased reactivity compared to the electron withdrawing groups and the di-arylated compounds **4h'** and **4i'** were obtained as the major products. Naphthyl (**4j**) and tri-fluorophenyl (**4k**) derivatives were also well-tolerated.

After exploring arylations directed by the piperidine moiety, we next investigated other possible saturated nitrogen-containing heterocyclic derivatives that could serve as effective directing groups for this transformation. Accordingly, the benzylic heterocycles **5a-f** were subjected to our previously optimised *ortho*-phenylation conditions. (Scheme 3) Gratifyingly, morpholine (**5a**) and piperazine (**5b** and **5c**) scaffolds worked well, affording the corresponding arylated products in good yield. Reactions with benzylic heterocycles of different ring size was also shown to be successful albeit the yield obtained was low under the standard conditions and no further optimisation was carried out to improve the yield.

In line with previous studies,¹⁴ we propose this C-H activation cross-coupling reaction proceeds *via* a Pd(II)/Pd(0) catalytic cycle (Fig. 3). The palladium species activates the *ortho* C-H of **1**, forming a 5-membered palladacycle intermediate **A**. Subsequently, addition of base is necessary for the transmetalation of Ar-Bpin to proceed to generate intermediate **B**. 1,4-benzoquinone then facilitates reductive elimination of the biaryl product **3** forming the Pd(0) species.^{14b,15} Reoxidation of Pd(0) by an oxidant, in this case Ag₂CO₃, is necessary for regeneration of the active Pd(II) species for further turnovers.



Scheme 3 C(sp²)-H cross-coupling of phenylboronic acid pinacol ester with functionalised benzylic heterocycles. ^a Reaction was carried out with **2a** (1.1 mmol) for 24 h.

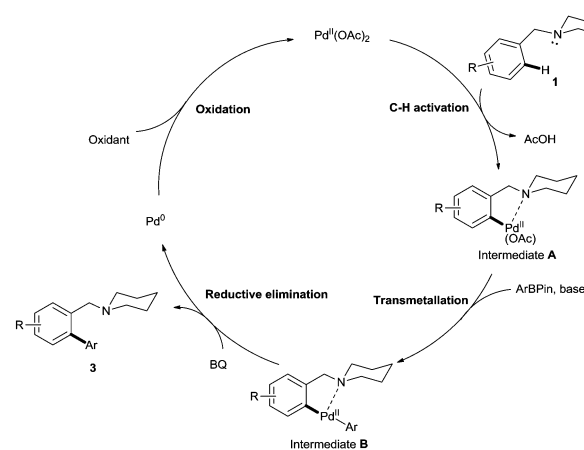


Fig. 3 Proposed C(sp²)-H arylation catalytic cycle.

In conclusion, we have demonstrated that a range of saturated nitrogen-containing heterocycles attached *via* the nitrogen atom to benzylic substrates serve as effective directing groups for palladium catalysed C(sp²)-H activation/arylation. Under palladium catalysis, the coupling of a range of arylboronic acid pinacol esters to the *ortho* position of *N*-benzylated pyrrolidines, piperidines, morpholine and piperazine substrates giving direct access, under relatively mild reaction conditions, to important biaryl motifs, was demonstrated. Investigations to develop the related direct *ortho* alkylation reaction are ongoing and our findings will be reported in due course.

The authors acknowledge the University of Oxford and the Agency of Science, Technology and Research (A*STAR) Singapore for a predoctoral fellowship. We also thank Dr Jayasree Seayad and Dr Vaibhav Mehta for their invaluable suggestions.

Notes and references

- (a) Cross-coupling reactions in organic synthesis, Themed issue, *Chem. Soc. Rev.*, 2011, **40**, 4977–5208 and references therein; (b) *Handbook of C-H Transformations*, ed. G. Dyker, Wiley-VCH, Weinheim, 2005; (c) J. F. Hartwig, *Organotransition Metal Chemistry*, University Science Books, 2009.



- 2 (a) C. C. C. J. Seechurn, M. O. Kitching, T. J. Calacot and V. Snieckus, *Angew. Chem., Int. Ed.*, 2012, **51**, 5062–5085; (b) *Modern Arylation Methods*, ed. L. Ackermann, Wiley-VCH, Weinheim, 2009.
- 3 (a) C–H functionalization in organic synthesis, Themed issue, *Chem. Soc. Rev.*, 2011, **40**, 1845–2040; (b) C–H functionalization, Themed issue, *Acc. Chem. Res.*, 2012, **45**, 777–958 and references cited therein; (c) J. Wencel-Delord, T. Droge, F. Liu and F. Glorius, *Chem. Soc. Rev.*, 2011, **40**, 4740–4761; (d) Directed C–H Functionalisation, Themed issue, *Adv. Synth. Catal.*, 2014, **356**, 1381–1644, and references therein; (e) J. Yamaguchi, A. D. Yamaguchi and K. Itami, *Angew. Chem., Int. Ed.*, 2012, **51**, 8960–9009.
- 4 (a) R. Giri, B.-F. Shi, K. M. Engle, N. Maugel and J.-Q. Yu, *Chem. Soc. Rev.*, 2009, **38**, 3242–3272; (b) A. J. Hickman and M. S. Sanford, *Nature*, 2012, **484**, 177–185; (c) J. Feng, G. Lu, M. Lv and C. Cai, *Synlett*, 2013, 2153–2159; (d) C. K. Seigerman, T. M. Micyus, S. R. Neufeldt and M. S. Sanford, *Tetrahedron*, 2013, **69**, 5580–5587; (e) Z.-J. Du, J. Guan, G.-J. Wu, P. Xu, L.-X. Gao and F.-S. Han, *J. Am. Chem. Soc.*, 2014, **137**, 632–635.
- 5 (a) X.-S. Zhang, K. Chen and Z.-J. Shi, *Chem. Sci.*, 2014, **5**, 2146–2159; (b) N. Kuhl, N. Schröder and F. Glorius, *Adv. Synth. Catal.*, 2014, **356**, 1443–1460; (c) G. Song, F. Wang and X. Li, *Chem. Soc. Rev.*, 2012, **41**, 3651–3678; (d) T. Satoh and M. Miura, *Chem. – Eur. J.*, 2010, **16**, 11212–11222.
- 6 (a) S. I. Kozhushkov and L. Ackermann, *Chem. Sci.*, 2013, **4**, 886–896; (b) P. B. Arockiam, C. Bruneau and P. H. Dixneuf, *Chem. Rev.*, 2012, **112**, 5879–5918; (c) L. Ackermann and R. Vicente, *Top. Curr. Chem.*, 2010, **292**, 211–229.
- 7 (a) A. Lazareva and O. Daugulis, *Org. Lett.*, 2006, **8**, 5211–5213. For free amine directed C(sp²)–H activation: (b) Z. Liang, L. Ju, Y. Xie, L. Huang and Y. Zhang, *Chem. – Eur. J.*, 2012, **18**, 15816–15821; (c) Z. Liang, J. Yao, K. Wang, H. Li and Y. Zhang, *Chem. – Eur. J.*, 2013, **19**, 16825–16831; (d) Z. Liang, R. Feng, H. Yin and Y. Zhang, *Org. Lett.*, 2013, **15**, 4544–4547.
- 8 (a) G. Cai, Y. Fu, Y. Li, X. Wan and Z.-J. Shi, *J. Am. Chem. Soc.*, 2007, **129**, 7666–7673; (b) For early report see: D. M. Grove, G. van Koten and H. J. C. Ubbels, *J. Am. Chem. Soc.*, 1982, **104**, 4285–4286.
- 9 H. Li, G.-X. Cai and Z.-J. Shi, *Dalton Trans.*, 2010, **39**, 10442–10446.
- 10 (a) R. Feng, J. Yao, Z. Liang, Z. Liu and Y. Zhang, *J. Org. Chem.*, 2013, **78**, 3688–3696; (b) D.-W. Gao, Y.-C. Shi, Q. Gu, Z.-L. Zhao and S.-L. You, *J. Am. Chem. Soc.*, 2013, **135**, 86–89; (c) For Ru(0)-catalysed *ortho*-silylation see: F. Kakiuchi, K. Igi, M. Matsumoto, T. Hayamizu, N. Chatani and S. Murai, *Chem. Lett.*, 2002, 396–397; (d) For dehydrogenative annulation see: H. Zhang, X. Cui, X. Yao, H. Wang, J. Zhang and Y. Wu, *Org. Lett.*, 2012, **14**, 3012–3015; (e) For Ir-catalysed borylation see: A. J. Roering, L. V. A. Hale, P. A. Squier, M. A. Ringgold, E. R. Wiederspan and T. B. Clark, *Org. Lett.*, 2012, **14**, 3558–3561.
- 11 B. B. Toure, K. Miller-Moslin, N. Yusuff, L. Perez, M. Dore, C. Joud, W. Michael, L. DiPietro, S. van der Plas, M. McEwan, F. Lenoir, M. Hoe, R. Karki, C. Springer, J. Sullivan, K. Levine, C. Fiorilla, X. Xie, R. Kulathila, K. Herlihy, D. Porter and M. Vaisser, *ACS Med. Chem. Lett.*, 2013, **4**, 186–190.
- 12 Z. Xin, H. Peng, A. Zhang, T. Talreja, G. Kumaravel, L. Xu, E. Rohde, M.-Y. Jung, M. N. Shackett, D. Kocisko, S. Chollate, A. W. Dunah, P. A. Snodgrass-Belt, A. Moore, A. G. Taveras, K. J. Rhodes and R. H. Scannevin, *Bioorg. Med. Chem. Lett.*, 2011, **21**, 7277–7280.
- 13 H. Choo, Y.-J. Kim, J. Kim and M. Y. Yeom, *US pat.*, 2014/0228568 A1, 2014.
- 14 (a) R. Giri, N. Maugel, J.-J. Li, D.-H. Wang, S. P. Breazzano, L. B. Saunders and J.-Q. Yu, *J. Am. Chem. Soc.*, 2007, **129**, 3510–3511; (b) M. Wasa, K. S. L. Chan and J.-Q. Yu, *Chem. Lett.*, 2011, **40**, 1004–1006; (c) K. M. Engle, P. S. Thuy-Boun, M. Dang and J.-Q. Yu, *J. Am. Chem. Soc.*, 2011, **133**, 18183–18193; (d) M. Wasa, K. M. Engle, D. W. Lin, E. J. Yoo and J.-Q. Yu, *J. Am. Chem. Soc.*, 2011, **133**, 19598–19601; (e) P. S. Thuy-Boun, G. Villa, D. Dang, P. F. Richardson, S. Su and J.-Q. Yu, *J. Am. Chem. Soc.*, 2013, **135**, 17508–17513; (f) K. S. L. Chan, M. Wasa, L. Chu, B. N. Laforteza, M. Miura and J.-Q. Yu, *Nat. Chem.*, 2014, **6**, 146–150; (g) K.-J. Xiao, D. W. Lin, M. Miura, R.-Y. Zhu, W. Gong, M. Wasa and J.-Q. Yu, *J. Am. Chem. Soc.*, 2014, **136**, 8138–8142.
- 15 (a) B. A. Steinhoff and S. S. Stahl, *J. Am. Chem. Soc.*, 2006, **128**, 4348–4355; (b) K. L. Hull and M. S. Sanford, *J. Am. Chem. Soc.*, 2007, **129**, 11904–11905; (c) K. L. Hull and M. S. Sanford, *J. Am. Chem. Soc.*, 2009, **131**, 9651–9653; (d) A. Ishikawa, Y. Nakao, H. Sato and S. Sakaki, *Dalton Trans.*, 2010, **39**, 3279–3289; (e) B. P. Carrow and J. F. Hartwig, *J. Am. Chem. Soc.*, 2011, **133**, 2116–2119.
- 16 In the case of product **3f**, attempts to improve reaction efficiency by the use of additional MPAA ligands (Boc-*L*-Thr-OH and Boc-*L*-Leu-OH) were unsuccessful and resulted in lower conversion.

