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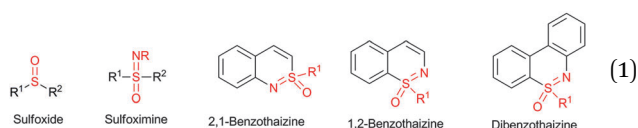
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Ruthenium- and palladium-catalyzed consecutive coupling and cyclization of aromatic sulfoximines with phenylboronic acids: an efficient route to dibenzothiazines†

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A ruthenium-catalyzed *ortho* arylation of aromatic sulfoximines with aromatic boronic acids followed by intramolecular cyclization in the presence of a palladium catalyst, providing dibenzothiazine derivatives in two consecutive steps, is described.

Sulfoximine is a pivotal structural motif which is present in various biologically active molecules, pharmaceuticals and agrochemicals (eqn (1)).¹ The sulfoximine derivatives are also successfully used as chiral auxiliaries and ligands in asymmetric synthesis of various chiral organic molecules.² Several methods are available in the literature to synthesize linear sulfoximine derivatives.³ But, the synthesis of cyclic sulfoximines is limited in the literature.⁴ Recently, the synthesis of cyclic sulfoximines has gained much attention in organic synthesis due to their usefulness as scaffolds in drug development and as chiral ligands in enantioselective reactions.⁵ Meanwhile, sulfoximine derivatives also serve as key synthetic intermediates in various organic transformations.^{5–7}

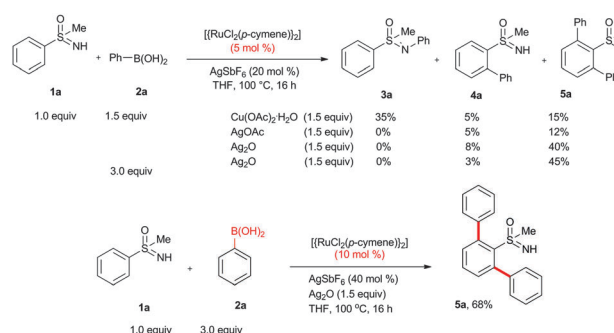


Harmata's group reported the synthesis of bicyclic sulfoximine derivatives such as 1,2-benzothiazine and 2,1-benzothiazine by palladium-catalyzed cyclization of 2-bromo benzaldehydes or 2-alkenylated aromatic bromides with sulfoximines, AlCl₃-mediated cyclization of sulfonimidoyl chlorides with alkynes or alkenes and electrophilic cyclization of 2-bromophenyl substituted sulfoximines with terminal alkynes in the presence of palladium and copper catalysts.⁶ Very recently, Bolm's group reported the synthesis of bicyclic 1,2-benzothiazine derivatives *via* rhodium-catalyzed oxidative cyclization^{7a} of phenyl sulfoximines with

alkynes *via* a chelation-assisted C–H bond activation reaction.^{8–10} Subsequently, sulfoximine directed *ortho* alkenylation of phenyl sulfoximines with alkenes in the presence of a metal catalyst was also disclosed.^{7b–e} In all these reports, sulfoximine containing bicyclic benzothiazine derivatives were synthesized efficiently.

Herein, we report the synthesis of tricyclic dibenzothiazines by a ruthenium-catalyzed *ortho* arylation of phenyl sulfoximines with aromatic boronic acids followed by intramolecular cyclization in the presence of a palladium catalyst in two consecutive steps. The present reaction was compatible with various sensitive and useful functional group substituted phenyl sulfoximines and aromatic boronic acids. An enantioselective version of *ortho* arylation of phenyl sulfoximines with phenylboronic acids followed by cyclization, and this transformation leads to chiral dibenzothiazines with an excellent ee ratio of 99%.

Initially, the *ortho* arylation of phenyl sulfoximine (**1a**) with phenylboronic acid (**2a**) (1.5 equiv.) in the presence of [[RuCl₂(*p*-cymene)]₂] (5 mol%), AgSbF₆ (20 mol%) and Cu(OAc)₂·H₂O (1.5 equiv.) in THF at 100 °C for 16 h was investigated (Scheme 1). In the reaction, *N*-arylated phenyl sulfoximine **3a** in 35% yield, mono *ortho* arylated phenyl sulfoximine **4a** in 5% yield and bis *ortho* arylated phenyl sulfoximine **5a** in 15% yield were observed, respectively (Scheme 1). It is known that the free N–H group of **1a** is acidic in nature and smoothly undergoes *N*-arylation with aromatic electrophiles or organometallic reagents



Scheme 1 *ortho* Arylation of sulfoximine **1a** with **2a**.

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providing *N*-arylated sulfoximines **3** in the presence of metal catalysts.¹¹ To successfully carry out the *ortho* arylation reaction, the suppression of product **3** is highly important. Next, the reaction was tested with other oxidants and acetate sources such as AgOAc, NaOAc, K₂CO₃, CsOAc and Ag₂O. Among them, silver salts such as AgOAc and Ag₂O were active for the reaction and no *N*-arylated product **3a** was observed. In AgOAc, product **4a** in 5% and **5a** in 12% yields were observed, respectively. In Ag₂O, product **4a** in 8% and **5a** in 40% yields were observed, respectively. Other acetate sources were not active for the reaction. Next, the coupling reaction was tested with an excess amount of phenylboronic acid **2a** (3.0 equiv.). In the reaction also, a mixture of products **4a** and **5a** were observed in 3% and 45% yields, respectively. To increase the yield of **5a**, the coupling reaction was performed in the presence of 10 mol% of catalyst and 40 mol% of AgSbF₆. Interestingly, in the reaction, only bis *ortho* arylated product **5a** was observed in 68% isolated yield and no mono arylated product **4a** was observed. For the detailed optimization studies, please see ESI.[†]

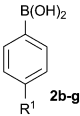
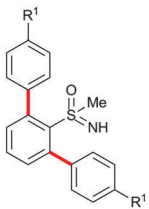
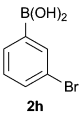
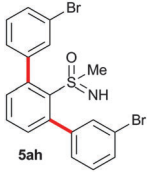
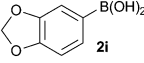
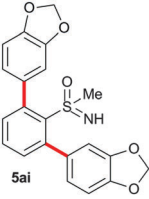
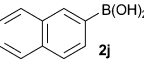
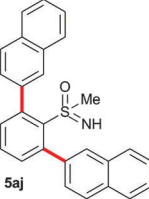
In addition to phenylboronic acid (**2a**), a wide range of aromatic boronic acids **2b–j** also readily participates in the reaction with **1a**. Table 1 summarizes the results of these reactions. Treatment of 4-phenyl substituted phenylboronic acid (**2b**) with **1a** provided *ortho* bis arylated product **5ab** in 72% yield (entry 1). Electron rich 4-methoxyphenyl boronic acid (**2c**) reacts smoothly with **1a**, yielding the corresponding product **5ac** in 66% yield (entry 2). Aromatic boronic acids having halogen groups I, Br, Cl and F **2d–g** also undergo an *ortho* arylation reaction with **1a** efficiently, giving products **5ad–ag** in 65%, 62%, 64% and 60% yields, respectively (entries 3–6). However, 3-bromo phenylboronic acid (**2h**) yielded product **5ah** only in 19% yield (entry 7). Benzo[*d*][1,3]dioxol-5-ylboronic acid (**2i**) and 2-naphthylboronic acid (**2j**) also efficiently participated in the reaction, affording coupling products **5ai** and **5aj** in 61% and 64% yields, respectively (entries 8 and 9).

The arylation reaction was examined with substituted aromatic sulfoximines **1b–g** (Scheme 2). Electron-rich, halogen and electron-deficient group substituted sulfoximines were compatible for the reaction. Methyl, Br and NO₂ substituted sulfoximines **1b–d** reacted with **2a**, providing products **5ba–da** in 65%, 63% and 54% yields, respectively. Similarly, Cl and F substituted aromatic sulfoximines **1e–f** reacted with **2c**, providing products **5ec–fc** in 60% and 63% yields, respectively. Likewise, (ethylsulfonylimidoyl)-benzene (**1g**) afforded **5ga** in 71% yield.

Apart from bis arylation, mono arylation of phenyl sulfoximines was also disclosed (Scheme 3). Treatment of 2-methyl phenylsulfoximine (**1h**) with **2a** or **2f** gave mono arylated sulfoximine derivatives **5ha** and **5he** in 70% and 63% yields, respectively. However, 3-methyl phenylsulfoximine (**1i**) afforded regioisomeric mono arylated products **5ia** and **5ia'** in 62% and 7% yields, respectively.

Next, we tried to couple the N–H bond of sulfoximine with one of the C–H bond of phenyl groups of compound **5** *via* chelation-assisted remote C–H activation in order to prepare tricyclic dibenzothiazine derivatives. A Pd(OAc)₂ catalyst along with an oxidant is the suitable condition for this type of cyclization.^{7c,12} The intramolecular cyclization of compound **5aa**

Table 1 Ruthenium-catalyzed *ortho* arylation of **1a** with aromatic boronic acids **2b–j**^a

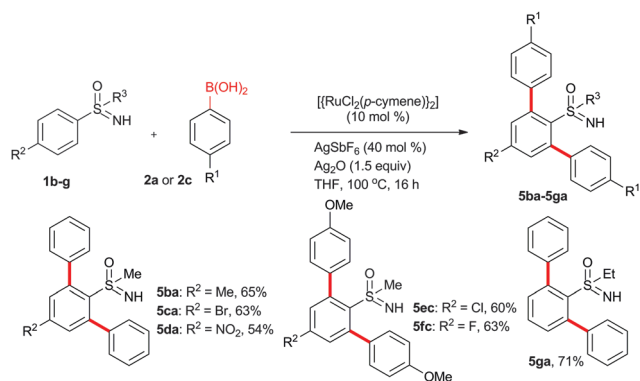
Entry	2b–j	Product 5	Yield ^b (%)
1			72
2	2c : R ¹ = OMe	5ac : R ¹ = OMe	66
3	2d : R ¹ = I	5ad : R ¹ = I	65
4	2e : R ¹ = Br	5ae : R ¹ = Br	62
5	2f : R ¹ = Cl	5af : R ¹ = Cl	64
6	2g : R ¹ = F	5ag : R ¹ = F	60
7			19
8			61
9			64

^a All reactions were carried out using **1a** (100 mg), aromatic boronic acids (**2b–j**) (3.0 equiv.), [RuCl₂(*p*-cymene)]₂ (10 mol%), AgSbF₆ (40 mol%), Ag₂O (1.5 equiv.) in THF (3.0 mL) at 100 °C for 16 h. ^b Isolated yield.

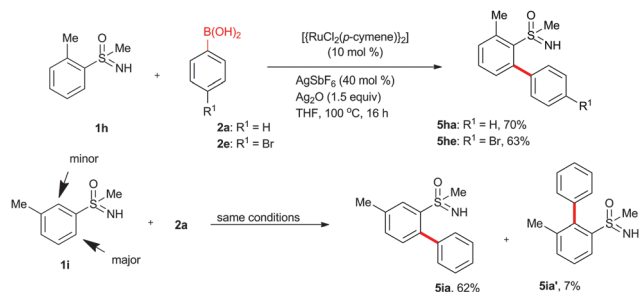
proceeded smoothly in the presence of Pd(OAc)₂ (10 mol%) and PhI(OAc)₂ (2.0 equiv.) in toluene at 120 °C for 10 h giving a tricyclic dibenzothiazine derivative **6a** in 76% yield (Table 2, entry 1). The cyclization reaction also proceeded in the presence of PhI(OAc)₂ without a palladium catalyst. However, product **6a** was observed in a less amount of 25% yield. Under similar reaction conditions, products **5ab**, **5ac**, **5ad**, **5ae**, **5af** and **5ag** also efficiently participated in the reaction, providing cyclization products **6b–g** in good to excellent yields (entries 2–7). Similarly, products **5ba**, **5ca**, **5da**, **5ga** and **5ha** afforded dibenzothiazines **6h–l** in 80%, 84%, 79%, 83% and 41% yields, respectively (entries 8–12). The structure of compound **6f** was further confirmed by single crystal X-ray analysis (see ESI[†]).

This result prompted us to explore the possibility of synthesis of chiral tricyclic dibenzothiazines by using chiral phenyl





Scheme 2 Scope of aromatic sulfoximines.

Scheme 3 Mono arylation of aromatic sulfoximines **1h-i**.

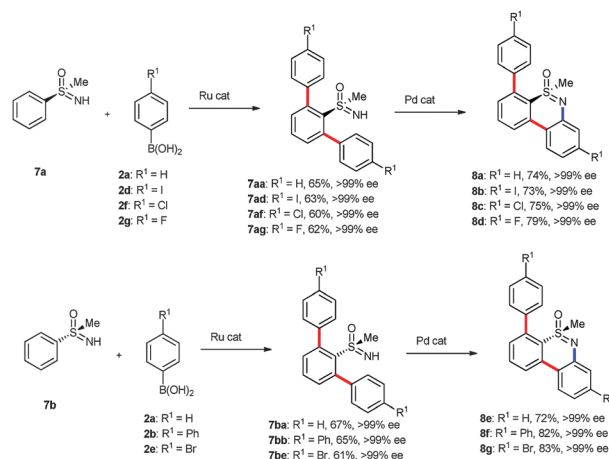
sulfoximines **7a-b** (Scheme 4). Treatment of chiral (*R*)-(-)-*S*-methyl-*S*-phenylsulfoximine (**7a**) with substituted phenyl boronic acids **2a**, **2d**, **2f** and **2g** in the presence of $[(RuCl_2(p\text{-cymene}))_2]$, $AgSbF_6$ and Ag_2O in THF at 100 °C for 16 h gave chiral *ortho* arylated phenyl sulfoximines **7aa-ag** in 65%, 63%, 60% and 62% yields, respectively (Scheme 4). Interestingly, the enantiomeric excess (ee) of products **7aa-ag** did not drop and in all cases > 99% ee ratios were observed. Later, compounds **7aa-ag** were cyclized into chiral dibenzothiazines **8a-d** in excellent 74%, 73%, 75% and 79% yields, respectively, in the presence of a palladium catalyst. In all these reactions, > 99% ee ratios were observed. Furthermore, (*S*)-(-)-*S*-methyl-*S*-phenylsulfoximine (**7b**) underwent *ortho* arylation with aromatic boronic acids **2a**, **2b** and **2e** in the presence of a ruthenium catalyst, providing chiral *ortho* arylated phenyl sulfoximines **7ba-be** in 67%, 65% and 61% yields, respectively, with > 99% ee ratios. Furthermore, **7ba-be** were converted into chiral dibenzothiazines **8e-g** in the presence of $Pd(OAc)_2$ in 72%, 82% and 83% yields, respectively.

A possible reaction mechanism is proposed to account for the present reaction in Scheme 5. Two different catalytic reactions were involved in the reaction. In the first catalytic cycle, $AgSbF_6$ likely removes all Cl^- ligands from the ruthenium complex providing a cationic ruthenium complex **9**.¹³ Coordination of the nitrogen atom of sulfoximine **1** into catalyst **9** followed by *ortho*-metalation provides a ruthenacycle intermediate **10**. Transmetalation of phenyl boronic acid **2** into intermediate **10** in the presence of Ag_2O affords intermediate **11**. Subsequent reductive elimination of intermediate **11** in the presence of Ag^+ source provides product **5** and regenerates the

Table 2 Synthesis of dibenzothiazines^a

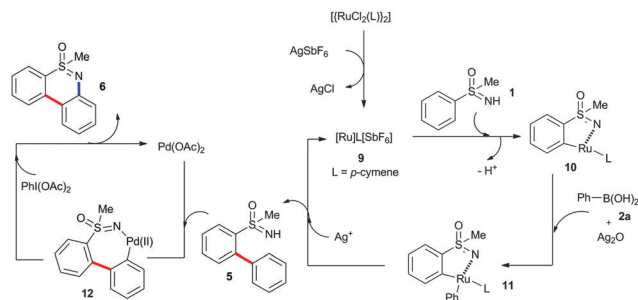
Entry	5	Product 6	Yield ^b (%)
1			76
2			85
3			65
4			77
5			85
6			79
7			81
8			80
9			84
10			79
11			83
12			41

^a All reactions were carried out using **5** (100 mg), $Pd(OAc)_2$ (10 mol %) and $PhI(OAc)_2$ (2.0 equiv.) in toluene at 120 °C for 10 h. ^b Isolated yield.



Scheme 4 Synthesis of chiral dibenzothiazines.





Scheme 5 Proposed mechanism.

active ruthenium species **9** for the next catalytic cycle. Another *ortho* arylation also takes place in a similar fashion. In the second catalytic cycle, compound **5** reacts with Pd(OAc)₂ giving palladacycle **12**. Reductive elimination of intermediate **12** in the presence of PhI(OAc)₂ provides cyclic product **6** and regenerates the active Pd(OAc)₂ catalyst for the next catalytic cycle. The exact role of Ag₂O is not clear to us, it could be possible that the AgO[−] anion acts as a base to accelerate the transmetalation of boronic acid **2** into intermediate **12** and the Ag⁺ ion acts as an oxidant to oxidize Ru(0) to Ru(II).

In conclusion, we have described a two-step synthesis of dibenzothiazines *via* a ruthenium-catalyzed *ortho* arylation of phenyl sulfoximines with phenyl boronic acids followed by intramolecular cyclization in the presence of Pd(OAc)₂. Chiral dibenzothiazines were prepared efficiently by using chiral phenyl sulfoximine in a similar protocol.

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Notes and references

- Bioactive sulfoximines: (a) H. Yu, Z. Qin, H. Dai, X. Zhang, X. Qin, T. Wang and J. Fang, *J. Agric. Food Chem.*, 2008, **56**, 1135; (b) D. Lu, Y. Y. Sham and R. Vince, *Bioorg. Med. Chem.*, 2010, **18**, 2037; (c) X. Y. Chen, S. J. Park, H. Buschmann, M. De Rosa and C. Bolm, *Bioorg. Med. Chem. Lett.*, 2012, **22**, 4307; (d) For a review, see: U. Lücking, *Angew. Chem., Int. Ed.*, 2013, **52**, 9399.
- Selected applications of chiral sulfoximines: (a) M. Haiza, J. Lee and J. K. Snyder, *J. Org. Chem.*, 1990, **55**, 5008; (b) X. Shen, W. Zhang, C. Ni, Y. Gu and J. Hu, *J. Am. Chem. Soc.*, 2012, **134**, 16999; (c) J. Brandt and H.-J. Gais, *Tetrahedron: Asymmetry*, 1997, **6**, 909.
- (a) M. A. M. Capozzi, C. Cardellicchio, F. Naso and P. Tortorella, *J. Org. Chem.*, 2001, **66**, 5933; (b) C. P. R. Hackenberger, G. Raabe and C. Bolm, *Chem. – Eur. J.*, 2004, **10**, 2942; (c) S. Pyne, *Sulfur Rep.*, 1992, **12**, 57; (d) C. R. Johnson, *Acc. Chem. Res.*, 1973, **6**, 341; (e) M. Gerisch, J. R. Krumper, R. G. Bergman and T. D. Tilley, *J. Am. Chem. Soc.*, 2001, **123**, 5818.
- (a) M. Harmata, Z. Cai and Y. Chen, *J. Org. Chem.*, 2009, **74**, 5559; (b) M. Harmata, R. J. Claassen and C. L. Barnes, *J. Org. Chem.*, 1991, **56**, 5059; (c) L. Wang, D. L. Priebebenow, X. Y. Chen, F.-F. Pan and C. Bolm, *Eur. J. Org. Chem.*, 2015, 3338; (d) M. Harmata and N. Pavri, *Angew. Chem., Int. Ed.*, 1999, **38**, 2419.
- (a) H.-J. Gais, *Heteroat. Chem.*, 2007, **18**, 472; (b) S. G. Pyne, Z. Dong, B. W. Skelton and A. H. White, *J. Org. Chem.*, 1997, **62**, 2337; (c) B. M. Trost and R. T. Matuoka, *Synlett*, 1992, 27; (d) M. Harmata and X. Hong, *J. Am. Chem. Soc.*, 2003, **125**, 5754.
- (a) M. Harmata and N. Pavri, *Angew. Chem., Int. Ed.*, 1999, **38**, 2419; (b) M. Harmata and X. Hong, *Tetrahedron Lett.*, 2005, **46**, 3847; (c) M. Harmata, K. Rayanil, M. G. Gomes, P. Zheng, N. L. Calkins, S.-Y. Kim, Y. Fan, V. Bumbu, D. R. Lee, S. Wacharasindhu and X. Hong, *Org. Lett.*, 2005, **7**, 143; (d) M. Harmata and E. O. Schlemper, *Tetrahedron Lett.*, 1987, **28**, 5997; (e) M. Harmata, R. J. Claassen and C. L. Barnes, *J. Org. Chem.*, 1991, **56**, 5059.
- (a) W. Dong, L. Wang, K. Parthasarathy, F. Pan and C. Bolm, *Angew. Chem., Int. Ed.*, 2013, **52**, 11573; (b) K. Parthasarathy and C. Bolm, *Chem. – Eur. J.*, 2014, **20**, 4896; (c) W. Dong, K. Parthasarathy, Y. Cheng, F. Pan and C. Bolm, *Chem. – Eur. J.*, 2014, **20**, 15732; (d) R. M. Yadav, R. K. Rit, M. Shankar and A. K. Sahoo, *J. Org. Chem.*, 2014, **79**, 6123; (e) M. Bhanuchandra, M. R. Yadav, R. K. Rit, M. R. Kuram and A. K. Sahoo, *Chem. Commun.*, 2013, **49**, 5225.
- (a) D. Alberico, M. E. Scott and M. Lautens, *Chem. Rev.*, 2007, **107**, 174; (b) G. P. McGlacken and L. M. Bateman, *Chem. Soc. Rev.*, 2009, **38**, 2447; (c) C.-L. Sun, B.-J. Li and Z.-J. Shi, *Chem. Rev.*, 2011, **111**, 1293; (d) O. Daugulis, H.-Q. Do and D. Shabashov, *Acc. Chem. Res.*, 2009, **42**, 1074; (e) L. Ackermann, R. Vicente and A. R. Kapdi, *Angew. Chem., Int. Ed.*, 2009, **48**, 9792; (f) D.-G. Yu, B.-J. Li and Z.-J. Shi, *Tetrahedron*, 2012, **68**, 5130; (g) P. B. Arockiam, C. Bruneau and P. H. Dixneuf, *Chem. Rev.*, 2012, **112**, 5879.
- (a) S. Ueno, N. Chatani and F. Kakiuchi, *J. Org. Chem.*, 2007, **72**, 3600; (b) F. Kakiuchi, S. Kan, K. Igi, N. Chatani and S. Murai, *J. Am. Chem. Soc.*, 2003, **125**, 1698; (c) L. Ackermann, R. Vicente and A. Althammer, *Org. Lett.*, 2008, **10**, 2299; (d) P. B. Arockiam, C. Fischmeister, C. Bruneau and P. H. Dixneuf, *Angew. Chem., Int. Ed.*, 2010, **49**, 6629.
- (a) C. G. Ravi Kiran and M. Jeganmohan, *Chem. Commun.*, 2014, **50**, 2442, references therein; (b) C. G. Ravi Kiran and M. Jeganmohan, *Org. Lett.*, 2012, **14**, 5246; (c) J. Hubrich, T. Himmler, L. Rodefeld and L. Ackermann, *Adv. Synth. Catal.*, 2015, **357**, 474; (d) V. K. Tiwari, N. Kamal and M. Kapur, *Org. Lett.*, 2015, **17**, 1766 Other metals: (e) S. Yang, B. Li, X. Wan and Z. Shi, *J. Am. Chem. Soc.*, 2007, **129**, 6066; (f) C.-L. Sun, B.-J. Li and Z.-J. Shi, *Chem. Commun.*, 2010, **46**, 677; (g) J. Karthikeyan, R. Haridharan and C.-H. Cheng, *Angew. Chem., Int. Ed.*, 2012, **51**, 12343; (h) N. Senthikumar, K. Parthasarathy, P. Gandeepan and C.-H. Cheng, *Chem. – Asian J.*, 2013, **8**, 2175; (i) S. Oi, S. Fukita and Y. Inoue, *Chem. Commun.*, 1998, 2439; (j) K. Ueura, T. Satoh and M. Miura, *Org. Lett.*, 2005, **7**, 2229.
- (a) C. Moessner and C. Bolm, *Org. Lett.*, 2005, **7**, 2667; (b) J. Kim, J. Ok, S. Kim, W. Choi and P. H. Lee, *Org. Lett.*, 2014, **16**, 4602; (c) N. Yongpruksa, N. L. Calkins and M. Harmata, *Chem. Commun.*, 2011, **47**, 7665; (d) M. Miyasaka, K. Hirano, T. Satoh, R. Kowalczyk, C. Bolm and M. Miura, *Org. Lett.*, 2011, **13**, 359.
- (a) W. C. P. Tsang, R. H. Munday, G. Brasche, N. Zheng and S. L. Buchwald, *J. Org. Chem.*, 2008, **73**, 7603; (b) P. Gandeepan, C.-H. Hung and C.-H. Cheng, *Chem. Commun.*, 2012, **48**, 9379; (c) B. Li, S. Tian, Z. Fang and Z. Shi, *Angew. Chem., Int. Ed.*, 2008, **47**, 1115; (d) M.-L. Louillat and F. W. Patureau, *Chem. Soc. Rev.*, 2014, **43**, 901.
- (a) E. Ferrer-Flegeau, C. Bruneau, P. H. Dixneuf and A. Jutand, *J. Am. Chem. Soc.*, 2011, **133**, 10161; (b) S. Warratz, C. Kornhaab, A. Cajaraville, B. Niepotter, D. Stalke and L. Accermann, *Angew. Chem., Int. Ed.*, 2015, **54**, 5513.

