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Cp*Rh(III)-catalyzed electrophilic amination of arylboronic acids with azo compounds for synthesis of arylhydrazides†

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A [Cp*Rh(III)]-catalyzed electrophilic amination of arylboronic acids with diethyl azodicarboxylate (DEAD) was developed, and arylhydrazides were produced in excellent yields and selectivity. The analogous amination with the arylazocarboxylates afforded the corresponding *N,N*-diarylhazides. The electrophilic amination of arylboronic acids with azocarboxylates proceeds readily under mild conditions with excellent functional group tolerance. Up to 99% yields were obtained. Preliminary mechanistic studies revealed that prior formation of an arylrhodium(III) intermediate for the azo coupling reaction can be ruled out.

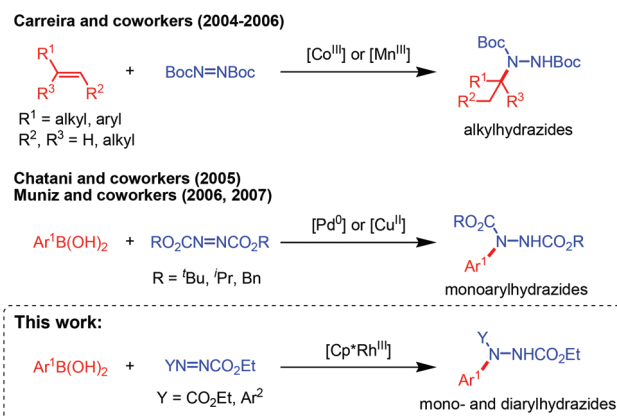
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Transition metal-catalyzed electrophilic (umpolung) aminations are attractive approaches for arylamine synthesis under mild conditions.¹ Characterized by weak N–X (X = leaving group) σ -bonds, haloamines and hydroxyamine derivatives have been extensively investigated for electrophilic amination with organolithium and -magnesium reagents.² Dialkyl azodicarboxylates are conceptually different classes of electrophilic amination reagents. Unlike the halo/hydroxyamine-type reagents, the azodicarboxylates react with carbanionic nucleophiles *via* N–N π -bond cleavage. While dialkyl azodicarboxylates are known to react with stoichiometric organometallic reagents for C–N bond coupling reactions,³ examples involving transition metal catalysis are sparse in the literature (Scheme 1). About a decade ago, Carreira and coworkers reported a Co- and Mn-catalyzed alkene hydrohydrazination using di-*tert*-butyl azodicarboxylate and triphenylsilane as reagents.^{3e–g} Recently, Chatani and coworkers reported a Cu-catalyzed hydroarylation of azodicarboxylates.^{3h} Muniz and coworkers reported a Pd-catalyzed coupling of arylboronic acids with diethyl azodicarboxylate (DEAD). A palladiaziridine complex was structurally characterized and was shown to mediate the C–N bond coupling reaction.^{3i,j}

Owing to an interest in developing transition metal catalyzed C–H bond aminations under mild conditions,⁴ we previously accomplished regioselective Pd-/Rh-catalyzed *ortho*-selective arene C–H amination with tosyloxycarbamates and *N*-chloroamines.^{4k–o} The catalytic arene C–H amination should



Scheme 1 Recent examples of transition metal-catalyzed electrophilic amination with azo reagents.

proceed by coupling of reactive arylpalladium(II) and -rhodium(III) complexes with the amination reagents. By virtue of the weak N–N π -bond, we envisioned that dialkyl azodicarboxylates would be effective coupling partners with aryl-metal complexes for C–N bond formation. Here we describe [Cp*Rh(III)]-catalyzed (Cp* = 1,2,3,4,5-pentamethyl-cyclopentadienyl) cross coupling of arylboronic acids with azo compounds for the synthesis of arylhydrazides.

When phenylboronic acid (**1a**; 0.3 mmol) was treated with DEAD (0.2 mmol) and [Cp*Rh(OAc)₂] (5 mol%) in THF at 80 °C under an N₂ atmosphere for 4 h, phenylhydrazide (**2a**) was obtained in 85% yield (Table 1, entry 1). In this work, we found that employing phenylboronic acid pinacol ester and potassium phenyltrifluoroborate alone did not bring about effective C–N coupling reactions (entries 2 and 3). The boron reagents were fully recovered with substantial decomposition

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Table 1 Reaction optimization^a

Entry	Aryl boron reagent	Catalyst	Solvent	T (°C)	Yield ^b (%)
1	PhB(OH) ₂ (1a)	[Cp*Rh(OAc) ₂]	THF	80	85
2	PhB(pin)	[Cp*Rh(OAc) ₂]	THF	80	n.d. ^c
3	KPhBF ₃	[Cp*Rh(OAc) ₂]	THF	80	n.d. ^c
4 ^d	KPhBF ₃	[Cp*Rh(OAc) ₂]	THF	80	70
5	1a	[Cp*RhCl ₂] ₂	THF	80	10
6	1a	[Rh(COD)Cl] ₂	THF	80	11
7	1a	[Rh(COD)(OH)] ₂	THF	80	n.d. ^c
8	1a	[Cp*IrCl ₂] ₂	THF	80	n.d. ^c
9	1a	[Cp*Rh(OAc) ₂]	^t BuOH	80	64
10	1a	[Cp*Rh(OAc) ₂]	MeCN	80	3
11	1a	[Cp*Rh(OAc) ₂]	Dioxane	80	50
12	1a	[Cp*Rh(OAc) ₂]	DCE	80	31
13 ^e	1a	[Cp*Rh(OAc) ₂]	DMF	40	99
14 ^f	1a	[Cp*Rh(OAc) ₂]	THF	80	42

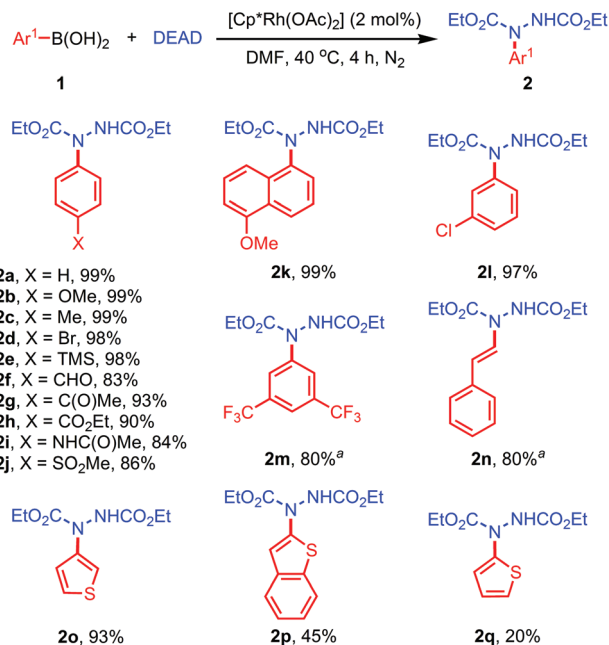
^a Conditions: aryl boron reagent (0.3 mmol), DEAD (0.2 mmol), catalyst (5 mol%), solvent (1 mL), 4 h in an N₂ atmosphere. ^b Isolated yield. ^c n.d. = not detected. ^d B(OH)₃ (0.3 mmol) was added. ^e [Cp*Rh(OAc)₂] (2 mol%) was used. ^f Di-*tert*-butyl azodicarboxylate (0.2 mmol) was used instead.

of the DEAD. Interestingly, when potassium phenyltrifluoroborate was employed together with B(OH)₃ as additives and DMF as the solvent, **2a** was formed in 70% yield (entry 4).

Other rhodium catalysts such as [Cp*RhCl₂]₂ are less effective catalysts (entry 5). According to the literature, rhodium(i) diene complexes such as [Rh(COD)X]₂ (X = Cl, OH) are known to catalyze arylation of enones with arylboron reagents.⁵ However, these Rh(i)-diene complexes were found to be ineffective catalysts for the reaction of **1a** with DEAD (entries 6 and 7). In this work, the related [Cp*IrCl₂]₂ complex exhibited negligible catalytic activities under our reaction conditions (entry 8).

Other solvents such as ^tBuOH, MeCN, dioxane and DCE gave inferior results compared to THF (entries 9–12). After several trials, we found that DMF gave the best result with **2a** being formed in a nearly quantitative yield.⁶ Upon further refinement of several experimental parameters, an optimized reaction protocol was established: [Cp*Rh(OAc)₂] (2 mol%), **1a** (0.3 mmol), DEAD (0.2 mmol) in DMF at 40 °C (entry 13). It is noteworthy that the azo coupling reaction is sensitive to the ester substituents on the azocarboxylates. For instance, the amination of **1a** with di-*tert*-butyl azodicarboxylate produced the corresponding arylhydrazides in only 42% yield (entry 14). The coupling with azobenzene was unsuccessful, and no C–N coupled products were obtained.⁶

With DEAD as the model substrate, the scope of the arylboronic acids was examined (Scheme 2). The reactions of arylboronic acids containing electron-donating and -withdrawing groups (e.g. OMe, Me and Br) afforded the corresponding hydrazides (**2a–2d**) in excellent yields. Other functionalized arylboro-



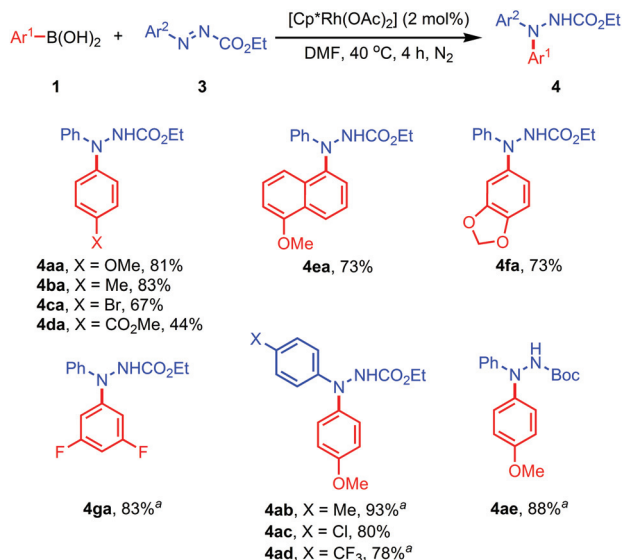
Scheme 2 Scope of the arylation of DEAD. Yields of isolated products are given. General reaction conditions: **1** (0.3 mmol), DEAD (0.2 mmol), [Cp*Rh(OAc)₂] (2 mol%), DMF (1 mL), 40 °C for 4 h in an N₂ atmosphere. ^aThe reaction was performed at 80 °C.

nic acids bearing TMS, CHO, C(O)Me, CO₂Et, NHC(O)Me and SO₂Me were converted to **2e–2j** in 83–98% yields. Fruitful results were achieved for the analogous amidation of 6-methoxy-1-naphthyl, 3-chloro and 3,5-bis(trifluoromethyl) phenylboronic acids with **2k–2m** being formed in excellent yields. Likewise, effective transformations of styrylboronic acid and heteroaromatic boronic acids were also achieved to give the corresponding products (**2n–2q**) in good to moderate yields.

Diarylamines are prevalent scaffolds found in many natural products, pharmaceuticals and functional materials.⁷ The Pd- and Cu-catalyzed arylation of anilines with haloarenes are widely employed for diarylamine synthesis.⁸ Yet, examples of diarylamine synthesis *via* electrophilic amination are sparse.⁹ Lei and coworkers reported the synthesis of diarylamines by Cu-catalyzed arylation of *N*-chloroanilides with arylboronic acids.^{9e} Recently, Chang and coworkers reported a reaction of aryl azides with aryliridium(III) complexes for diarylamine synthesis.^{9f–h} In this work, we developed the catalytic arylation of arylazocarboxylates for the synthesis of *N,N*-diaryldihydrazides.

The arylazocarboxylate was prepared by reacting arylhydrazine with ethyl chloroformate, followed by NBS oxidation. When phenylazocarboxylate (**3a**) was treated with 4-methoxyphenylboronic acid (**1b**) and [Cp*Rh(OAc)₂] (2 mol%) in DMF at 40 °C under an N₂ atmosphere, *N,N*-diaryldihydrazides (**4aa**) was isolated as a single regioisomer in 81% yield (Scheme 3). The molecular structure of **4aa** has been established by single-crystal X-ray crystallography. Arylboronic acids containing elec-





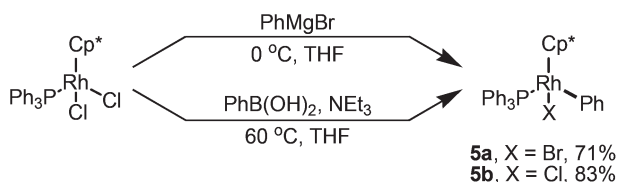
Scheme 3 Scope of the arylation of arylazocarboxylate. Yields of isolated products are given. General reaction conditions: **1** (0.3 mmol), **3** (0.2 mmol), [Cp^{*}Rh(OAc)₂] (2 mol%), DMF (1 mL), 40 °C for 4 h in an N₂ atmosphere. ^aThe reaction was performed at 80 °C.

tron-donating and -withdrawing substituents were well tolerated (see results for **4ba–4da**). Similarly, amidation of 6-methoxy-1-naphthyl, 3,4-(methylenedioxy) and 3,5-ditrifluorophenylboronic acids furnished **4ea–4ga** in excellent yields.

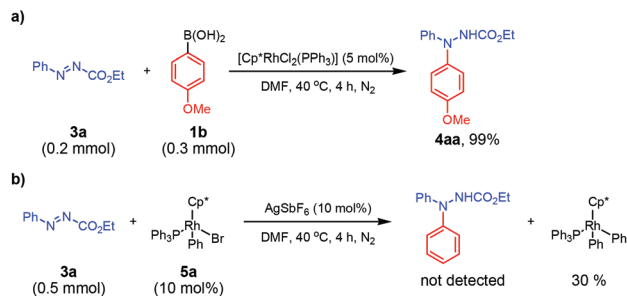
With 4-methoxyphenylboronic acid as the arylating reagent, the reactions of some substituted arylazocarboxylates were examined. Effective C–N coupling was observed in all cases, and the diarylhydrazides (**4ab–4ae**) were formed in 78–93% yields.

Arylrhodium(III) complexes are known to mediate catalytic C–N bond coupling reactions.^{4m,10} To examine the involvement of the arylrhodium(III) complexes, we prepared the well-defined [Cp^{*}Rh(Ph)(Br)(PPh₃)] complex **5a** (71% yield) by reacting [Cp^{*}RhCl₂(PPh₃)] with PhMgBr.¹¹ The analogous [Cp^{*}Rh(Ph)(Cl)(PPh₃)] complex **5b** (83% yield) was also prepared by employing phenylboronic acid as the aryl source (Scheme 4).¹² The molecular structures of **5a** and **5b** have been confirmed by single-crystal X-ray crystallography.⁶

In this work, when [Cp^{*}Rh(Ph)(Br)(PPh₃)] (**5a**) (10 mol%) was treated with AgSbF₆ (10 mol%) and phenylazocarboxylate (0.5 mmol) in DMF at 40 °C for 4 h, no *N,N*-diphenylhydrazide was formed. Notably, [Cp^{*}Rh(Ph)₂(PPh₃)] was isolated in 30% yield, and 18% of the starting [Cp^{*}Rh(Ph)(Br)(PPh₃)] was recov-



Scheme 4 Synthesis of [Cp^{*}Rh(Ph)(X)(PPh₃)].



Scheme 5 Investigation of the stoichiometric reaction of arylrhodium(III) complexes with phenylazocarboxylate.

ered (Scheme 5). Notwithstanding, [Cp^{*}RhCl₂(PPh₃)] was found to be an effective catalyst for the arylation reaction. For example, reacting [Cp^{*}RhCl₂(PPh₃)] (5 mol%) with 4-methoxyphenylboronic acid (**1b**) and phenylazocarboxylate (**3a**) in DMF at 40 °C afforded **4aa** in 99% yield. Based on the above findings, direct coupling of arylrhodium(III) with the azo reagent may not be a productive step for the arylation reaction.

Previously, Muniz and coworkers reported the Pd-catalyzed arylation of DEAD by arylboronic acids, and palladadiaziridine complexes have been characterized as the key intermediate. However, the attempt to characterize well-defined rhodalladiaziridine complexes was unsuccessful. The preparation and characterization of some reactive metalladiaziridine complexes are currently in progress, and the results will be reported separately.

Conclusions

In conclusion, we developed a [Cp^{*}Rh(III)]-catalyzed electrophilic amination of arylboronic acids by employing azo reagents. Effective coupling of DEAD and the aryl azocarboxylates with arylboronic acids afforded mono- and diarylhydrazides in good yields under mild conditions.

Acknowledgements

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Notes and references

- For transition metal-catalyzed electrophilic amination, see: (a) A. Ricci, *Amino Group Chemistry: From Synthesis to the Life Sciences*, Wiley-VCH, Weinheim, 2008; (b) A. Ricci, *Modern Amination Methods*, Wiley-VCH, Weinheim, 2000.
- For a selected review on electrophilic amination of carbanions, see: (a) E. Erdik and M. Ay, *Chem. Rev.*, 1989, **89**, 1947. For selected articles on the stoichiometric addition of organometallic reagents: for the use of organolithium reagents, see: (b) P. Beak and B. J. Kokko, *J. Org. Chem.*,



- 1982, **47**, 2823. For the use of Grignard reagents, see: (c) M. J. Campbell and J. S. Johnson, *Org. Lett.*, 2007, **9**, 1521; (d) E. Erdik and S. Ates, *Synth. Commun.*, 2006, **36**, 2813; (e) M. Kitamura, T. Suga, S. Chiba and K. Narasaka, *Org. Lett.*, 2004, **6**, 4619. For the use of organozinc reagents, see: (f) A. M. Berman and J. S. Johnson, *J. Org. Chem.*, 2006, **71**, 219; (g) A. M. Berman and J. S. Johnson, *J. Org. Chem.*, 2005, **70**, 364; (h) E. Erdik and T. J. Daskapan, *Chem. Soc., Perkin Trans. 1*, 1999, 3139. For the use of cuprates, see: (i) P. Bernardi, P. Dembech, G. Fabbri, A. Ricci and G. Seconi, *J. Org. Chem.*, 1999, **64**, 641; (j) A. Alberti, F. Cane, P. Dembech, D. Lazzari, A. Ricci and G. Seconi, *J. Org. Chem.*, 1996, **61**, 1677; (k) A. Casarini, P. Dembech, D. Lazzari, E. Marini, G. Reginato, A. Ricci and G. Seconi, *J. Org. Chem.*, 1993, **58**, 5620. For the use of organostannane reagents, see: (l) Z. Zhang, Y. Yu and L. S. Liebeskind, *Org. Lett.*, 2008, **10**, 3005.
- 3 For stoichiometric addition of organometallic reagents reacting with azo compounds: for the use of Grignard reagents, see: (a) I. Sapountzis and P. Knochel, *Angew. Chem., Int. Ed.*, 2004, **43**, 897. For the use of organozinc reagents, see: (b) P. Sinha, C. C. Kofink and P. Knochel, *Org. Lett.*, 2006, **8**, 3741; (c) H. Mitchell and Y. Leblanc, *J. Org. Chem.*, 1994, **59**, 682. For the use of organotitanium reagents, see: (d) D. K. An, K. Hirakawa, S. Okamoto and F. Sato, *Tetrahedron Lett.*, 1999, **40**, 3737. For transition metal catalyzed C–N bond formation employing azo compounds: for Co- and Mn-catalyzed alkene hydrohydrazination, see: (e) J. Waser, B. Gaspar, H. Nambu and E. M. Carreira, *J. Am. Chem. Soc.*, 2006, **128**, 11693; (f) J. Waser, J. C. Gonzalez-Gomez, H. Nambu, P. Huber and E. M. Carreira, *Org. Lett.*, 2005, **7**, 4249; (g) J. Waser and E. M. Carreira, *J. Am. Chem. Soc.*, 2004, **126**, 5676. For Cu-mediated C–N bond coupling of arylboronic acid with azo compounds, see: (h) T. Uemura and N. Chatani, *J. Org. Chem.*, 2005, **70**, 8631. For Pd-catalyzed C–N bond coupling of arylboronic acid with azo compounds, see: (i) K. Muniz and A. Iglesias, *Angew. Chem., Int. Ed.*, 2007, **46**, 6350; (j) K. Muniz and M. Nieger, *Angew. Chem., Int. Ed.*, 2006, **45**, 2305.
- 4 Here our recent studies on catalytic C–H bond cross coupling reactions are depicted. For transition metal-catalyzed *ortho*-selective arene C–H bond carbenoid insertion, see: (a) H.-W. Lam, K.-Y. Man, W.-W. Chan, Z. Zhou and W.-Y. Yu, *Org. Biomol. Chem.*, 2014, **12**, 4112; (b) W.-W. Chan, S.-F. Lo, Z. Zhou and W.-Y. Yu, *J. Am. Chem. Soc.*, 2012, **134**, 13565; (c) W.-W. Chan, T.-L. Kwong and W.-Y. Yu, *Org. Biomol. Chem.*, 2012, **10**, 3749; (d) W.-W. Chan, S.-H. Yeung, Z. Zhou, A. S. C. Chan and W.-Y. Yu, *Org. Lett.*, 2010, **12**, 604. For transition metal-catalyzed *C2-ortho*-selective arene C–H bond coupling with carbonyl radical, see: (e) C.-W. Chan, P.-Y. Lee and W.-Y. Yu, *Tetrahedron Lett.*, 2015, **56**, 2559; (f) W.-W. Chan, Z. Zhou and W.-Y. Yu, *Chem. Commun.*, 2013, **49**, 8214; (g) C.-W. Chan, Z. Zhou and W.-Y. Yu, *Adv. Synth. Catal.*, 2011, **353**, 2999; (h) C.-W. Chan, Z. Zhou, A. S. C. Chan and W.-Y. Yu, *Org. Lett.*, 2010, **12**, 3926; (i) W.-Y. Yu, W. N. Sit, Z. Zhou and A. S. C. Chan, *Org. Lett.*, 2009, **11**, 3174; (j) W.-Y. Yu, W. N. Sit, K.-M. Lai, Z. Zhou and A. S. C. Chan, *J. Am. Chem. Soc.*, 2008, **130**, 3304. For Pd-catalyzed *ortho*-selective arene C–H bond amination with tosylloxycarbamates, see: (k) K.-H. Ng, F.-N. Ng and W.-Y. Yu, *Chem. Commun.*, 2012, **48**, 11680; (l) K.-H. Ng, A. S. C. Chan and W.-Y. Yu, *J. Am. Chem. Soc.*, 2010, **132**, 12862. For Rh-catalyzed *ortho*-selective arene C–H amination with *N*-chloramines, see: (m) F.-N. Ng, Z. Zhou and W.-Y. Yu, *Chem. – Eur. J.*, 2014, **20**, 4474; (n) K.-H. Ng, Z. Zhou and W.-Y. Yu, *Chem. Commun.*, 2013, **49**, 7031; (o) K.-H. Ng, Z. Zhou and W.-Y. Yu, *Org. Lett.*, 2012, **14**, 272.
- 5 For selective examples of rhodium(i) diene complexes catalyzed arylation of enones, see: (a) S. Gosiewska, J. A. Raskatov, R. Shintani, T. Hayashi and J. M. Brown, *Chem. – Eur. J.*, 2012, **18**, 80; (b) H. J. Edwards, J. D. Hargrave, S. D. Penrose and C. G. Frost, *Chem. Soc. Rev.*, 2010, **39**, 2093; (c) R. Shintani and T. Hayashi, *Aldrichimica Acta*, 2009, **42**, 31; (d) T. Hayashi, K. Ueyama, N. Tokunaga and K. Yoshida, *J. Am. Chem. Soc.*, 2003, **125**, 11508.
- 6 Refer to the ESI† for detailed experimental data.
- 7 (a) A. Kleeman, J. Engel, B. Kutscher and D. Reichert, *Pharmaceutical Substances: Syntheses, Patents, Applications of the most relevant APIs*, Thieme, Stuttgart, 5th edn, 2009; (b) S. M. Wilhelm, L. Adnane, P. Newell, A. Villanueva, J. M. Llovet and M. Lynch, *Mol. Cancer Ther.*, 2008, **7**, 3129; (c) R. Sordella, D. W. Bell, D. A. Haber and J. Settleman, *Science*, 2004, **305**, 1163; (d) M. W. N. Deininger and B. J. Druker, *Pharmacol. Rev.*, 2003, **55**, 401.
- 8 For Pd-catalyzed nucleophilic amination for diarylamine synthesis, see: (a) F. Paul, J. Patt and J. F. Hartwig, *Organometallics*, 1995, **14**, 3030; (b) A. S. Guram, R. A. Rennels and S. L. Buchwald, *Angew. Chem.*, 1995, **107**, 1456, (*Angew. Chem. Int. Ed. Engl.*, 1995, **34**, 1348); (c) J. Louie and J. F. Hartwig, *Tetrahedron Lett.*, 1995, **36**, 3609; (d) F. Paul, J. Patt and J. F. Hartwig, *J. Am. Chem. Soc.*, 1994, **116**, 5969. For Cu-catalyzed nucleophilic amination for diarylamine synthesis, see: (e) D. M. T. Chan, K. L. Monaco, R.-P. Wang and M. P. Winters, *Tetrahedron Lett.*, 1998, **39**, 2933; (f) D. A. Evans, J. L. Katz and T. R. West, *Tetrahedron Lett.*, 1998, **39**, 2937; (g) P. Y. S. Lam, C. G. Clark, S. Saubern, J. Adams, M. P. Winters, D. M. T. Chan and A. Combs, *Tetrahedron Lett.*, 1998, **39**, 2941.
- 9 For transition metal-catalyzed electrophilic amination for diarylamine synthesis: for stoichiometric addition of organoaluminum reagents reacting with *O*-protected hydroxamic acid, see: (a) S. Zhou, Z. Yang, X. Chen, Y. Li, L. Zhang, H. Fang, W. Wang, X. Zhu and S. Wang, *J. Org. Chem.*, 2015, **80**, 6323; (b) H. Yoon and Y. Lee, *J. Org. Chem.*, 2015, **80**, 10244. For Cu-catalyzed electrophilic amination for diarylamine synthesis, see: (c) R. Sakae, K. Hirano and M. Miura, *J. Am. Chem. Soc.*, 2015, **137**, 6460; (d) T. Kawano, K. Hirano, T. Satoh and M. Miura, *J. Am. Chem. Soc.*, 2010, **132**, 6900; (e) C. He, C. Chen, J. Cheng, C. Liu, W. Liu, Q. Li and A. Lei, *Angew. Chem., Int. Ed.*, 2008, **47**, 6414. For Rh-



- catalyzed electrophilic amination for diarylamine synthesis, see: (f) S. H. Park, J. Kwak, K. Shin, J. Ryu, Y. Park and S. Chang, *J. Am. Chem. Soc.*, 2014, **136**, 2492; (g) K. Shin, Y. Baek and S. Chang, *Angew. Chem., Int. Ed.*, 2013, **52**, 1; (h) J. Ryu, K. Shin, S. H. Park, J. Y. Kim and S. Chang, *Angew. Chem., Int. Ed.*, 2012, **51**, 9904.
- 10 For arylrhodium(III)-mediated catalytic C–N bond coupling reactions, see: (a) G. Song, F. Wang and X. Li, *Chem. Soc. Rev.*, 2012, **41**, 3651; (b) K. Shin, Y. Baek and S. Chang, *Angew. Chem., Int. Ed.*, 2013, **52**, 1; (c) C. Grohmann, H. Wang and F. Glorius, *Org. Lett.*, 2012, **14**, 656; (d) J. Y. Kim, S. H. Park, J. Ryu, S. H. Cho, S. H. Kim and S. Chang, *J. Am. Chem. Soc.*, 2012, **134**, 9110; (e) C. Grohmann, H. Wang and F. Glorius, *Org. Lett.*, 2013, **15**, 3014. For arylrhodium(III)-mediated catalytic carbenoid C–C bond coupling reactions, see: (f) Y.-S. Lu and W.-Y. Yu, *Org. Lett.*, 2016, **18**, 1350; (g) F.-N. Ng, Y.-F. Lau, Z. Zhou and W.-Y. Yu, *Org. Lett.*, 2015, **17**, 1676.
- 11 J. W. Kang, K. Moseley and P. M. Maitlis, *J. Am. Chem. Soc.*, 1969, **91**, 5970.
- 12 E. J. Farrington, C. F. J. Barnard, E. Rowsell and J. M. Brown, *Adv. Synth. Catal.*, 2005, **347**, 185.

