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Selective and Serial Suzuki–Miyaura Reactions of Polychlorinated Aromatics with Alkyl Pinacol Boronic Esters

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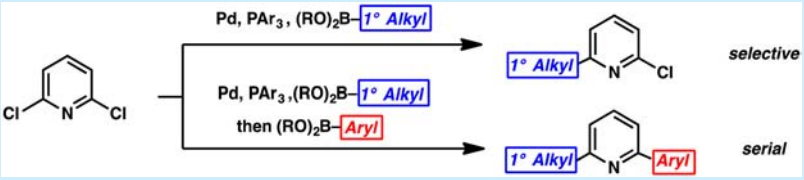
Supporting Information



ABSTRACT: Among cross-coupling reactions, the Suzuki–Miyaura transformation stands out because of its practical advantages, including the commercial availability and low toxicity of the required reagents, mild reaction conditions, and functional group compatibility. Nevertheless, few conditions can be used to cross-couple alkyl boronic acids or esters with aryl halides, especially 2-pyridyl halides. Herein, we describe two novel Suzuki–Miyaura protocols that enable selective conversion of polychlorinated aromatics, with a focus on reactions to convert 2,6-dichloropyridines to 2-chloro-6-alkylpyridines or 2-aryl-6-alkylpyridines.

The 2-alkylpyridyl motif is critically important within natural products, pharmaceutical agents, fragrances, ligands for catalysis, molecular electronic devices, and biomimetic scaffolds (Figure 1).[1] Several powerful strategies

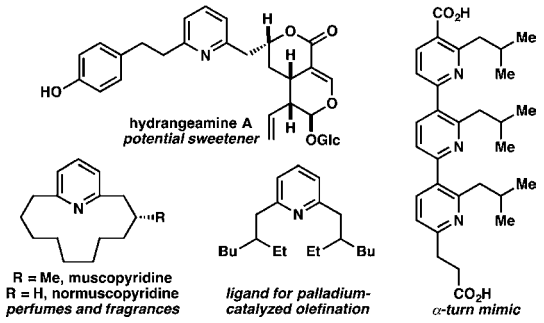
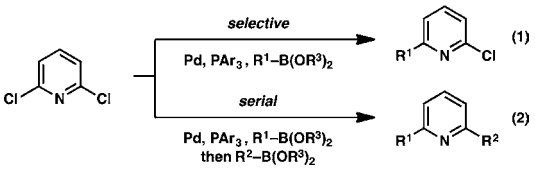


Figure 1. Alkylpyridine motifs are critical. Glc = D-glucose.[1]

have been reported recently to form new $C(sp^2)–C(sp^3)$ bonds in order to access substituted pyrdines.[2−5] In terms of cross-coupling reactions, access to 2-pyridyl organometallic reagents[6,7] is imperfect,[8] as most remain difficult to isolate or have limited stability. Additionally, many of the associated reactions require toxic reagents or prove ineffective with primary alkyl electrophiles. By contrast, heteroaryl chlorides are readily accessible, but have remained challenging substrates[9,10] particularly in Suzuki–Miyaura[10,11] reactions. Herein, we disclose systems for the reaction of bench stable alkyl pinacol boronic esters with aryl chlorides, with a focus on polyhalogenated 2-pyridyl chlorides. Polyhalogenated six-membered heteroarenes[12] react with predictable selectivity (Scheme 1, eq 1) and undergo successive cross-coupling reactions with distinct organoboron compounds to generate two new carbon–carbon bonds serially in a single reaction vessel (eq 2).

Scheme 1. Selective and Serial Reactions



Owing to their relatively low cost and broad commercial availability, heteroaryl chlorides offer practical value over heteroaryl bromides and iodides as substrates in Suzuki–Miyaura reactions. Nevertheless, this transformation is challenging due to (1) the strength of aryl chloride bonds relative to aryl iodide or bromide bonds[13] and (2) the ability of heteroatoms to coordinate to and inhibit the reactivity of transition metal catalysts. Alkylboron reagents add to these challenges as they can contribute to formation of undesired byproducts through protodeboronation, protodehalogenation, oxidation, and homocoupling.

To overcome these limitations, we chose to focus on the reaction of 2,6-dichloropyridine (**1a**) with heptyl pinacol boronic ester (**2a**). We sought conditions to generate 2-chloro-6-alkylpyridine **3a** selectively (Table 1). The optimal conditions would not furnish *exhaustively* cross-coupled 2,6-dialkylpyridine **4a**.

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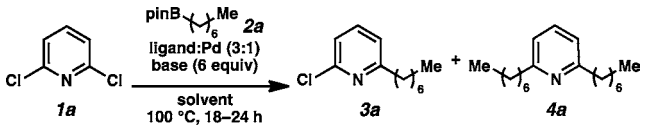
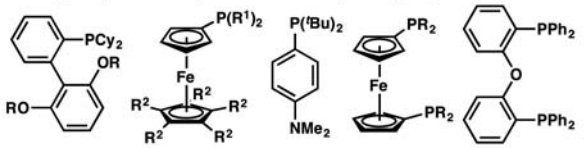
Table 1. Reaction Optimization



entry	Pd source	ligand	solvent	base	3a (%)[a]	4a (%)[a]
1[b,c]	$Pd(dba)_2$	RuPhos	PhMe/H_2O	NaO^{t}Bu	6	0
2[b,d]	$Pd_2(dba)_3$	RuPhos	PhMe/H_2O	NaO^{t}Bu	0	0
3[b]	$Pd(dba)_2$	Q-Phos	dioxane/H_2O	CsF	0	0
4[b]	$PdCl_2A^{ta}Phos_2$		dioxane/H_2O	Cs_2CO_3	10	0
5[e]	$PdCl_2$(DPEPhos)		dioxane/H_2O	K_3PO_4	62	1
6[e]	$PdCl_2$(dcpf)		dioxane/H_2O	K_3PO_4	26	1
7[e]	$PdCl_2$(dppf)		dioxane/H_2O	K_3PO_4	50	1
8[e]	$Pd_2(dba)_3$	o-$MeOC_6H_4PPh_2$	dioxane/H_2O	K_3PO_4	76	12
9[e]	**$Pd_2(dba)_3$**	**$FcPPh_2$**	**dioxane/H_2O**	**K_3PO_4**	**74**	**1**
10[e,f]	$Pd_2(dba)_3$	PPh_3	dioxane/H_2O	K_3PO_4	21	13



[a]Determined by ^{1}H NMR. [b]5 mol % Pd. [c]80 °C. [d]110 °C. [e]1 mol % Pd. [f]2-Heptylpyridine (14% yield) was detected by ^{1}H NMR.

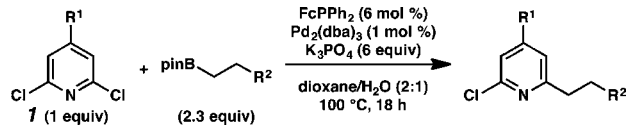
The targeted bond-forming reaction proceeds with poor efficiency using many of the cutting-edge protocols designed to couple aryl halides with organoboron compounds (entries 1–4).[14] We anticipated that use of sterically encumbered bidentate phosphine ligands would promote the desired reaction.[15] Indeed, some bidentate ligands furnish 2-chloro-6-heptylpyridine (**3a**, entries 5–7).

The denticity of these bidentate ligands is not critical to reaction efficiency. When a monodentate analogue of DPEPhos, (*o*-$MeOC_6H_4$)PPh_2, is employed, high catalyst turnover numbers are achieved, though reaction selectivity erodes (entry 8). Under the optimal conditions, a monodentate analogue of dppf, $FcPPh_2$, is used as a ligand. To the best of our knowledge $FcPPh_2$ has been described only once as a ligand for Suzuki–Miyaura reactions,[16] though more sterically encumbered analogues are in common use.[17] Under the optimal conditions, 2,6-dichloropyridines react with heptyl boronic pinacol ester in 2:1 dioxane/H_2O at 100 °C with K_3PO_4 as a base, 1 mol % $Pd_2(dba)_3$, and 6 mol % $FcPPh_2$ to afford desired 2-chloro-6-heptylpyridine (**3a**) in excellent selectivity and 74% isolated yield (entry 9).[18]

$FcPPh_2$ proves to be more effective in this reaction than many standard ligands, including PPh_3 (entry 10). Relative to a phenyl group, the ferrocenyl group is more sterically encumbering[19] and better able to stabilize adjacent partial positive charge.[20] These features have great effect, as PPh_3 furnishes desired **3a** in only 21% ^{1}H NMR yield.

Under these selective conditions, chloropyridines react in good yields with alkyl pinacol boronic esters that are saturated, or incorporate distal functional groups including an olefin, an acetal masked aldehyde, and a primary alkyl chloride (Table 2). These conditions are tolerant of nitro and ketone functional groups, transforming electron-deficient chlorobenzene analogues efficiently (Table 3, entries 1, 2).

Table 2. Tolerated Functional Group Variations



entry[a]	ArCl	pinB–R²	product	yield (%)[b]
1	**1a**, R^1 = H	n = 6		**3a**,74
2[c]	R^1 = CF_3	n = 6		**3b**,61
3	R^1 = Cl	n = 6		**3c**,56
4	**1a**	n = 3		**3d**,65
5	**1a**	**2c**		**3e**,77
6	R^1 = CH_3			**3f**, 79
7	**1a**			**3g**,63
8	**1a**			**3h**,72
9[c]	**1a**			**3i**, 65
10[c,e]				**3j**, 81[d]

[a]General reaction conditions: 1.0 equiv of aryl chloride, 0.13 M dioxane/H_2O (2:1), 2.3 equiv of $R^2(CH_2)_2Bpin$, 1 mol % $Pd_2(dba)_3$, 6 mol % $FcPPh_2$, 6.0 equiv of K_3PO_4, 18 h, 100 °C. [b]Isolated yield. [c]48 h. [d]Isolated after reaction with trifluoroacetic acid. [e]1.5 equiv of $R^2(CH_2)_2Bpin$, 3.0 equiv of K_3PO_4.

Electronic perturbations influence reactivity: electron-rich 4-chloroanisole does not react under these conditions (Table 3, entry 3).

These conditions face expected limitations in terms of substrate scope. Aromatic compounds that are sensitive to the combination of water and base, such as 2,4- and 2,5-dichloropyrimidine, degrade under the reaction conditions.

The reaction proceeds selectively to generate the 2-chloro-6-alkylpyridine rather than the 2,6-dialkylpyridine. In principle, the selectivity of the reaction may arise from the 6-alkyl substituent performing the following roles: (a) hindering precoordination of the catalyst by sterically shielding the pyridine nitrogen, (b) raising the transition state barrier for oxidative addition based on sterically induced strain,[21] (c) disfavoring transmetalation by sterically encumbering the reactive aryl–Pd species, or (d) increasing the barrier to oxidative addition or transmetalation electronically. To evaluate these possibilities, we probed the differences in substrate reactivity (Table 3). If the steric size of the alkyl substituent were the principal determinant of selectivity, we would expect to see statistical mixtures of coupled products for substrates with distal chlorides, yet these substrates couple selectively (entries 4–6).

Furthermore, these conditions affect the chemoselective reaction of 1,3-dichloroisoquinoline at the more sterically encumbered C(1) position (entry 7). The observed selectivity complements known reactions to install an aryl group at C(1).[22] Moreover, this selectivity has been predicted[21,23,24] and rationalized by comparing the expected bond dissociation energies of 1,3-dichloroisoquinoline at C(1) and C(3).[21] This

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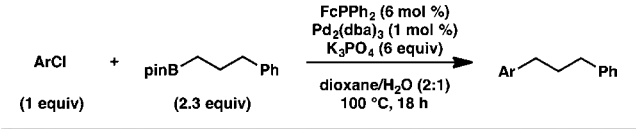
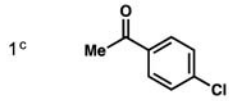
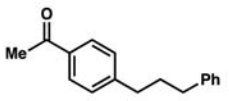
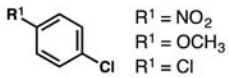
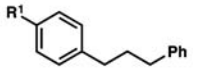
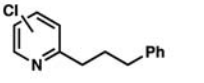
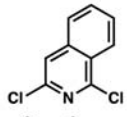
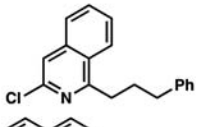
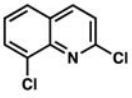
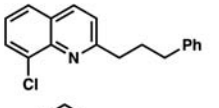
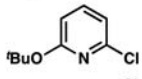
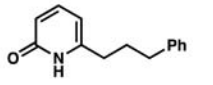
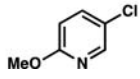
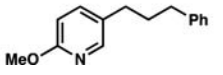
Table 3. Selectivity Based on Electronic Bias



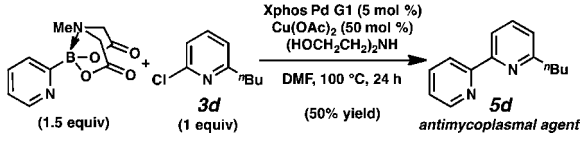
entry[a]	ArCl	product	yield (%)[b]
1[c]			*3k*, 69
2[c]	 R¹ = NO₂		*3l*, 91
3[c]	R¹ = OCH₃		*3m*, nd[d]
4	R¹ = Cl		*3n*, 47[e]
5	 3-Cl		*3o*, 85
6	5-Cl		*3p*, 80
7[f]			*3q*, 69
8			*3r*, 73
9[c]			*3s*, 98[g]
10			*3t*, nd,[c, d] 24[h]

[a]General reaction conditions: 1.0 equiv of aryl chloride, 0.13 M dioxane/H_2O (2:1), 2.3 equiv of $R^2(CH_2)_2Bpin$, 1 mol % $Pd_2(dba)_3$, 6 mol % $FcPPh_2$, 6.0 equiv of K_3PO_4, 18−20 h, 100 °C. [b]Isolated yield. [c]1.5 equiv of $R^2(CH_2)_2Bpin$, 3.0 equiv of K_3PO_4. [d]Not detected by ^1H NMR. [e]Exhaustively coupled product (6% yield) was detected by crude ^1H NMR. [f]48 h. [g]Isolated after reaction with trifluoroacetic acid. [h]2 mol % $Pd_2(dba)_3$, 12 mol % $FcPPh_2$.

same logic predicts that 2,8-dichloroquinoline will undergo cross-coupling at C(2), as is observed (entry 8).

As selectivity is not principally steric in origin, electron donation by the new alkyl substituent must increase the barrier either to oxidative addition or to transmetalation. This hypothesis is consistent with the remarkably efficient transformation of 2-chloro-6-*tert*-butoxypyridine, which incorporates an inductively withdrawing group *meta*- to the activated C−Cl bond (entry 9), and the diminished reactivity of 5-chloro-2-methoxypyridine, which includes a resonance donating group *para*- to the targeted C−Cl bond (entry 10).

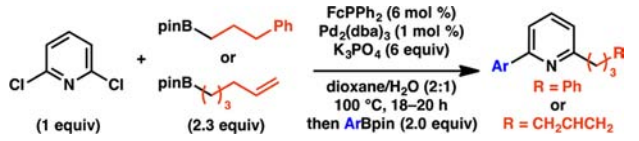
Scheme 2. Serial Cross-Coupling Transformations

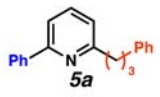
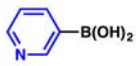
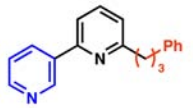
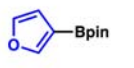
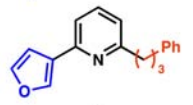
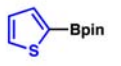
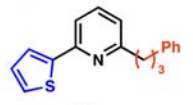
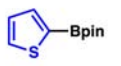
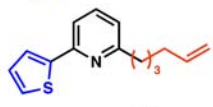
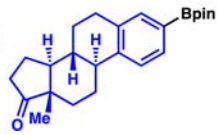
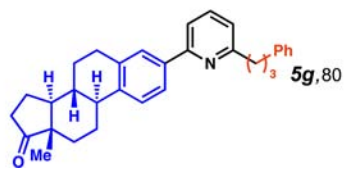


The power of this cross-coupling method can be demonstrated through the combination of our method with Burke's conditions[6d] to transform 2,6-dichloropyridine to an antimycoplasmal agent[25] (Scheme 2) via 2-chloro-6-butylpyridine (Table 2, entry 4).

We sought to merge the selective method with a compatible reaction, which would obviate the need to isolate the 2-chloro-6-alkylpyridine intermediate. The resultant one-pot serial reaction relies on the rapid rate of transmetalation of arylboron compounds relative to alkylboron reagents (Table 4). These conditions transform a wide range of

Table 4. Iterative Cross-Coupling Reactions



entry[a]	organoboron	product	yield (%)[b]
1	$PhB(OH)_2$	 *5a*	80
2	PhBpin		78, 76[c]
3	PhB(MIDA)		78
4	$PhBF_3K$		75
5			*5b*, 68
6			*5c*, 67
7			*5e*, 62
8			*5f*, 75
9			*5g*, 80

[a]General reaction conditions: 1.0 equiv of aryl chloride, 0.13 M dioxane/H_2O (2:1), 2.3 equiv of $R^2(CH_2)_2Bpin$, 1 mol % $Pd_2(dba)_3$, 6 mol % $FcPPh_2$, 6.0 equiv of K_3PO_4, 18 h, 100 °C then 2.0 equiv of organoboron reagent, 18−20 h unless noted. [b]Isolated yield. [c]5 h.

arylboron compounds, including arylboronic acids and esters, trifluoroborate salts,[26] and *N*-methyl-iminodiacetic acid (MIDA) boronate esters[27] (entries 1−4). The reaction can convert furyl, thiophenyl, and pyridyl boron compounds, as well as an estrone derivative (entries 6−9) to furnish high value differently substituted pyridines efficiently.

The disclosed methods couple inexpensive and readily available chloroaryl subunits with bench and air stable pinacol boronic esters. A chemoselective transformation mediated by $FcPPh_2/Pd_2(dba)_3$ predictably and selectively converts polychlorinated pyridine or benzene starting materials to monoalkylated products. These conditions allow efficient access to an antimycoplasmal agent. Additionally, a one-pot sequential Suzuki−Miyaura reaction of alkyl- and then arylboron compounds has been developed to access differentially substituted pharmacologically relevant motifs.

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■ ASSOCIATED CONTENT

Supporting Information

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Full experimental details, copies of NMR spectra (PDF)

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Notes

The authors declare no competing financial interest.

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■ REFERENCES

(1) (a) Liu, J.; Nakamura, S.; Matsuda, H.; Yoshikawa, M. *Tetrahedron Lett.* **2013**, *54*, 32−34. (b) Schinz, H.; Ruzicka, L.; Geyer, U.; Prelog, V. *Helv. Chim. Acta* **1946**, *29*, 1524−1528. (c) Zhang, Y.-H.; Shi, B.-F.; Yu, J.-Q. *J. Am. Chem. Soc.* **2009**, *131*, 5072−5074. (d) Davis, J. M.; Truong, A.; Hamilton, A. D. *Org. Lett.* **2005**, *7*, 5405−5408.

(2) Goetz, A. E.; Garg, N. K. *Nat. Chem.* **2013**, *5*, 54−60.

(3) For select examples that involve distinct bond-forming and deprotonation steps, see: (a) Jeffrey, J. L.; Sarpong, R. *Org. Lett.* **2012**, *14*, 5400−5403. (b) Chen, Q.; León, T.; Knochel, P. *Angew. Chem., Int. Ed.* **2014**, *53*, 8746−8750. (c) Hyodo, I.; Tobisu, M.; Chatani, N. *Chem. - Asian J.* **2012**, *7*, 1357−1365.

(4) (a) Lewis, J. C.; Bergman, R. G.; Ellman, J. A. *J. Am. Chem. Soc.* **2007**, *129*, 5332−5333. (b) Nakao, Y.; Yamada, Y.; Kashihara, N.; Hiyama, T. *J. Am. Chem. Soc.* **2010**, *132*, 13666−13668.

(5) For select Minisci-type pathways, see: (a) Jin, J.; MacMillan, D. W. C. *Nature* **2015**, *525*, 87−90. (b) Gianatassio, R.; Kawamura, S.; Eprile, C. L.; Foo, K.; Ge, J.; Burns, A. C.; Collins, M. R.; Baran, P. S. *Angew. Chem., Int. Ed.* **2014**, *53*, 9851−9855. (c) O'Hara, F.; Blackmond, D. G.; Baran, P. S. *J. Am. Chem. Soc.* **2013**, *135*, 12122−12134.

(6) For select 2-pyridyl zinc reagents, see: (a) Cornella, J.; Edwards, J. T.; Qin, T.; Kawamura, S.; Wang, J.; Pan, C.-M.; Gianatassio, R.; Schmidt, M.; Eastgate, M. D.; Baran, P. S. *J. Am. Chem. Soc.* **2016**, *138*, 2174−2177. (b) Colombe, J. R.; Bernhardt, S.; Stathakis, C.; Buchwald, S. L.; Knochel, P. *Org. Lett.* **2013**, *15*, 5754−5757. (c) Luzung, M. R.; Patel, J. S.; Yin, J. *J. Org. Chem.* **2010**, *75*, 8330−8332. For select 2-pyridyl boron reagents, see: (d) Dick, G. R.; Woerly, E. M.; Burke, M. D. *Angew. Chem., Int. Ed.* **2012**, *51*, 2667−2672. (e) Sakashita, S.; Takizawa, M.; Sugai, J.; Ito, H.; Yamamoto, Y. *Org. Lett.* **2013**, *15*, 4308−4311. (f) Billingsley, K. L.; Buchwald, S. L. *Angew. Chem., Int. Ed.* **2008**, *47*, 4695−4698. For 2-pyridyl tin reagents, see: (g) Littke, A. F.; Schwarz, L.; Fu, G. C. *J. Am. Chem. Soc.* **2002**, *124*, 6343−6348. (h) Bailey, T. R. *Tetrahedron Lett.* **1986**, *27*, 4407−4410. For 2-pyridyl aluminum reagents, see: (i) Chen, X.; Zhou, L.; Li, Y.; Xie, T.; Zhou, S. *J. Org. Chem.* **2014**, *79*, 230−239.

(7) For a select coupling reaction, see: Llaveria, J.; Leonori, D.; Aggarwal, V. K. *J. Am. Chem. Soc.* **2015**, *137*, 10958−10961.

(8) (a) Old, D. W.; Wolfe, J. P.; Buchwald, S. L. *J. Am. Chem. Soc.* **1998**, *120*, 9722−9723. (b) Wolfe, J. P.; Singer, R. A.; Yang, B. H.; Buchwald, S. L. *J. Am. Chem. Soc.* **1999**, *121*, 9550−9561.

(9) For select Negishi and Kumada reactions, see: (a) Malhotra, S.; Seng, P. S.; Koenig, S. G.; Deese, A. J.; Ford, K. A. *Org. Lett.* **2013**, *15*, 3698−3701. (b) Fürstner, A.; Leitner, A. *Angew. Chem., Int. Ed.* **2003**, *42*, 308−311. (c) Getmanenko, Y. A.; Twieg, R. J. *J. Org. Chem.* **2008**, *73*, 830−839. For cross-electrophile reactions, see: (d) Everson, D. A.; Buonomo, J. A.; Weix, D. J. *Synlett* **2014**, *25*, 233−238.

(10) (a) Martin, R.; Buchwald, S. L. *Acc. Chem. Res.* **2008**, *41*, 1461−1473. (b) Billingsley, K.; Anderson, K. W.; Buchwald, S. L. *Angew. Chem., Int. Ed.* **2006**, *45*, 3484−3488. (c) Li, L.; Zhao, S.; Joshi-Pangu, A.; Diane, M.; Biscoe, M. R. *J. Am. Chem. Soc.* **2014**, *136*, 14027−14033. (d) Jouffroy, M.; Primer, D. N.; Molander, G. A. *J. Am. Chem. Soc.* **2016**, *138*, 475−478.

(11) (a) Miyaura, N.; Suzuki, A. *Chem. Rev.* **1995**, *95*, 2457−2483. (b) Lennox, A. J. J.; Lloyd-Jones, G. C. *Chem. Soc. Rev.* **2014**, *43*, 412−443.

(12) (a) Rossi, R.; Bellina, F.; Lessi, M. *Adv. Synth. Catal.* **2012**, *354*, 1181−1255. (b) Fairlamb, I. *Chem. Soc. Rev.* **2007**, *36*, 1036−1045.

(13) (a) Bedford, R. B.; Cazin, C. S. J.; Holder, D. *Coord. Chem. Rev.* **2004**, *248*, 2283−2321. (b) Littke, A. F.; Fu, G. C. *Angew. Chem., Int. Ed.* **2002**, *41*, 4176−4211.

(14) (a) Li, Q.; Liskey, C. W.; Hartwig, J. F. *J. Am. Chem. Soc.* **2014**, *136*, 8755−8765. (b) Yang, C. T.; Zhang, Z. Q.; Tajuddin, H.; Wu, C. C.; Liang, J.; Liu, J. H.; Fu, Y.; Czyzewska, M.; Steel, P. G.; Marder, T. B.; Liu, L. *Angew. Chem., Int. Ed.* **2012**, *51*, 528−532. (c) Fleury-Bregeot, N.; Presset, M.; Beaumard, F.; Colombel, V.; Oehlrich, D.; Rombouts, F.; Molander, G. A. *J. Org. Chem.* **2012**, *77*, 10399−10408.

(15) Hartwig, J. F. *Synlett* **2006**, *2006*, 1283−1294.

(16) Milde, B.; Lohan, M.; Schreiner, C.; Ruffer, T.; Lang, H. *Eur. J. Inorg. Chem.* **2011**, *2011*, 5437−5449.

(17) (a) Pickett, T. E.; Roca, F. X.; Richards, C. J. *J. Org. Chem.* **2003**, *68*, 2592−2599. (b) Liu, S.-Y.; Choi, M. J.; Fu, G. C. *Chem. Commun.* **2001**, 2408−2409.

(18) The mass balance for this reaction is principally accounted for by starting material and the desired product.

(19) Otto, S. *J. Chem. Crystallogr.* **2001**, *31*, 185−190.

(20) Allenmark, S. *Tetrahedron Lett.* **1974**, *15*, 371−374.

(21) Legault, C. Y.; Garcia, Y.; Merlic, C. A.; Houk, K. N. *J. Am. Chem. Soc.* **2007**, *129*, 12664−12665 and references therein..

(22) Ford, A.; Sinn, E.; Woodward, S. *J. Chem. Soc., Perkin Trans. 1* **1997**, 927−934.

(23) Handy, S. T.; Zhang, Y. *Chem. Commun.* **2006**, 299−301.

(24) Garcia, Y.; Schoenebeck, F.; Legault, C. Y.; Merlic, C. A.; Houk, K. N. *J. Am. Chem. Soc.* **2009**, *131*, 6632−6639.

(25) Pijper, P. J.; Van der Goot, H.; Timmerman, H.; Nauta, W. T. *Eur. J. Med. Chem.* **1984**, *19*, 399−404.

(26) Molander, G. A. *J. Org. Chem.* **2015**, *80*, 7837−7848.

(27) (a) Mancilla, T.; Contreras, R.; Wrackmeyer, B. *J. Organomet. Chem.* **1986**, *307*, 1−6. (b) Li, J.; Grillo, A. S.; Burke, M. D. *Acc. Chem. Res.* **2015**, *48*, 2297−2307.

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