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Copper-Catalyzed Aerobic Oxidative Amination of C(sp3)-H bonds: Synthesis of Imidazo[1, 5-*a*]pyridines

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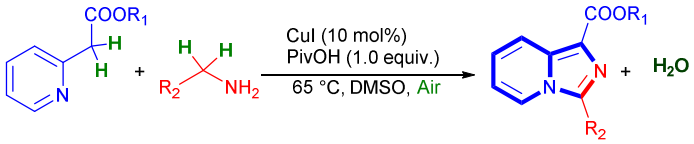
Copper-catalyzed synthesis of imidazo[1, 5-*a*]pyridine-1-carboxylates through oxidative amination of C(sp3)-H bonds under mild aerobic conditions with broad substrate scope is described. Use of naturally abundant air as a sole oxidant found to be efficient and selective. The present protocol is also applicable for direct synthesis of functionalized imidazo[1, 5-*a*]pyridines from amino acid derivatives.

Transition metal catalyzed C−H bond amination via a step-economic and environmental methods are significant strategies for the synthesis of azaheterocycles.[1] Recently, various transition metal catalysts have been developed for C−H bond amination which including ruthenium[2] rhodium[3] and palladium based[4] systems, where stoichiometric or excess amount of oxidants were employed. The use of molecular oxygen for copper-catalyzed aerobic oxidative C-H bond activation for C-N bond formations are highly attractive[5] due to the large abundance of oxygen, low cost and avoids the formation of toxic by-products.[6]

Imidazo[1, 5-*a*]pyridine (**IP**) scaffolds are found in many pharmacologically important compounds.[7] Other applications of these derivatives also have been actively probed in the context of organic light-emitting diodes (OLED)[8] and organic thin layer field effect transistors (FET).[9] In addition, 2-azaindolizines have been examined as pharmaceuticals (eg, HIV-protease inhibitors)[10] as precursors of *N*-heterocyclic carbenes[11] and additionally, several metal complexes have been reported.[12] However, only limited synthetic routes are available to access these molecules. The reported methods mainly relied on the traditional Vilsmeier-type cyclizations of *N*-2-pyridylmethylamides.[13] Recent reports available for synthesis of imidazo[1,5-a]pyridines with stoichiometric amount of iodine source in presence of excess of oxidant[14&15] and other methods.[16] Therefore, developing of more practical and efficient synthetic routes for imidazo[1,5-a]pyridines is highly desirable. In continuation of our efforts on the development of green and sustainable methods for the synthesis of azaheterocycles,[17] we report herein an efficient copper catalyzed aerobic oxidative amination of C(sp3)-H bonds for the synthesis imidazo[1,5-a]pyridine derivatives utilising molecular oxygen (O_2) from air as sole oxidant which generates only water as by-product in the system, which makes this transformation more atom-economical and importantly sustainable than the reported methods (Scheme 1)



Scheme 1.

We started our investigation on the oxidative amination of C (sp3)-H bonds by choosing tert-butyl 2-(pyridin-2-yl) acetate **1a** and 4-chlorobenzylamine **2a** as model substrates (Table 1). Initially, the reaction of **1a** and **2a** was performed employing CuI (10 mol %) as catalyst, in DMSO at room temperature in open air, trace amount of tert-butyl 3-(4-chlorophenyl) imidazo [1, 5-a] pyridine-1-carboxylate **3a** was observed (Table 1, entry 1). The same reaction was carried out with 0.1 equivalent of acetic acid as additive; **3a** was isolated in 15% yield (Table 1, entry 2). The product **3a** was further conformed by single crystal XRD (fig.S1).

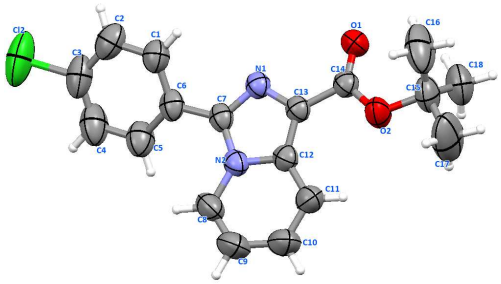


Figure S1.

To uphold the reaction yield, it was conducted at 45 °C and 65 °C; the yield was also increased (Table 1, entries 3 & 4). Further

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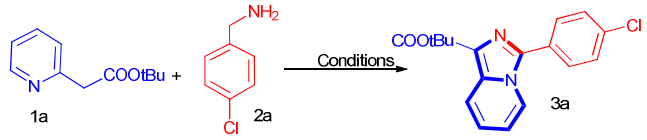
increasing the amount of additive to 1.0 equivalent at 65 °C, **3a** was isolated in 80% yield (Table 1, entry 5). Use of trifluoroacetic acid (TFA) as additive the yield was decreased (Table 1, entry 6). With pivalicacid (PivOH) as additive, **3a** was isolated in 91% yield (Table 1, entry 7). When the temperature of the reaction was further increased to 80 °C, yet, same the yield (91%) was observed (Table 1, entry 8). At the optimum temperature of 65 °C, it was performed without additive to check the efficiency of the reaction, but yield was reduced to 38 % (Table 1, entry 9). The reaction was also performed with other copper salts (CuBr, CuCl, $CuCl_2$, $Cu(OAc)_2$ and $Cu(OTf)_2$) (Table 1, entries 10-14) as well as solvents (DMF, dioxan, ACN and chlorobenzene) (Table1, entries 15-18) they found to be less effective. Under these conditions reactions were either poorly effective or entirely ineffective (Table1, entries 10-18). Further, under the conditions of entry 7, reaction was performed by using oxygen atmosphere (balloon) instead of open air; the yield of **3a** was decreased to 76 % (Table 1, entry 19). It may be due to the

Table 1. Optimization of reaction conditions for 3a[a]

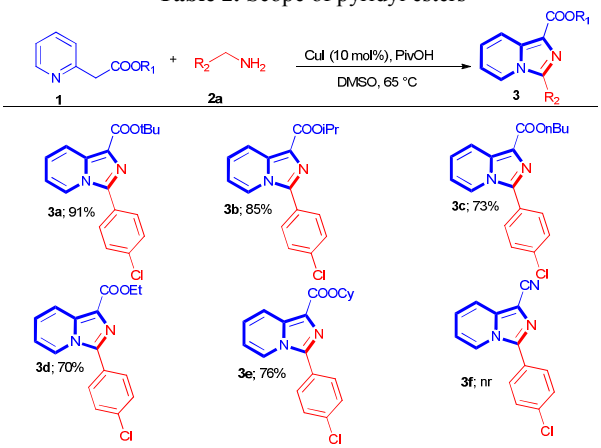


Entry	CuX (10 mol%)	Additive/Oxidant	Solvent	Temperature	Yield [%][b]
1	CuI	–/air	DMSO	rt	Trace
2[c]	CuI	AcOH/Air	DMSO	rt	15
3[c]	CuI	AcOH/Air	DMSO	45	32
4[c]	CuI	AcOH/Air	DMSO	65	51
5	CuI	AcOH/Air	DMSO	65	80
6	CuI	TFA/Air	DMSO	65	62
7	**CuI**	**PivOH/Air**	**DMSO**	**65**	**91**
8	CuI	PivOH/Air	DMSO	80	91
9	CuI	–/Air	DMSO	65	38
10	CuBr	PivOH/Air	DMSO	65	84
11	CuCl	PivOH/Air	DMSO	65	87
12	$CuCl_2$	PivOH/Air	DMSO	65	67
13	$Cu(OAc)_2$	PivOH/Air	DMSO	65	62
14	$Cu(OTf)_2$	PivOH/Air	DMSO	65	25
15	CuI	PivOH/Air	DMF	65	64
16	CuI	PivOH/Air	Dioxane	65	Trace
17	CuI	PivOH/Air	Acetonitrile	65	Trace
18	CuI	PivOH/Air	Chlorobenzene	65	27
19	CuI	PivOH/O_2	DMSO	65	76
20	CuI	PivOH/Ar	DMSO	65	15
21	--	PivOH/Air	DMSO	65	nr

[a]Reaction conditions: **1a** (0.25 mmol), **2a** (0.50 mmol), Additive (0.25 mmol), catalyst (0.025 mmol), solvent (1 mL), in an oil bath under open air, 15 h. [b]Isolated yield. [c] 0.1 Equiv. of additive is used. [nr = no reaction].

conversion of benzyl amine to imine under aerobic conditions.[18] Reaction under argon atmosphere, only 15% of **3a** was isolated (Table 1, entry 20). Entries 19 and 20 indicate that, oxygen from open air was found to be effective and selective oxidant for the present transformation. Also, without catalyst, no reaction under the same experimental conditions (Table 1, entry 21). Hence, the optimized reaction conditions identified for the present investigation was 10 mol% CuI, 1.0 equivalents of PivOH as additive, at 65 ºC, in DMSO under open air (Table 1, entry 7). Hear

Table 2. Scope of pyridyl esters[a]



[a]Reaction conditions; 1 (0.25 mmol), 2a (0.5 mmol), Additive (0.25 mmol), catalyst (0.025 mmol) Solvent (1 mL), in an oil bath under air, isolated yield, nr: no reaction .

Under the optimised conditions, the scope of the copper-catalysed (sp3) C-H amination followed by annulation of **2a** with various pyridyl esters **1** was investigated. The results can be seen in Table 2; ester groups such as –COO^{t}Bu, -COO^{i}Pr, -COO^{n}Bu, -COOEt, and -COOCy, were well tolerated. The reaction proceeded very well and provided the desired products **3a-3e** in good to high yields. However, 2-(pyridin-2-yl) acetonitrile did not give the desired product (**3f**).

To extend the synthetic scope of this method, a variety of pyridyl esters **1** and substituted benzylamines **2** were subjected to these optimized conditions. As can be seen from the results of Table 3; electron-withdrawing groups as well as electron-donating groups were well tolerated. In general, the reaction of **1a** with benzylamine bearing both electron-donating and withdrawing substituents on the aromatic ring proceeded very well and gave the desired products **4b-4m** in good to high yields (74-95%). It may be noted that, halide (Cl, Br and F) substituted imidazo[1,5-a]pyridine derivatives were well tolerated, and provided the corresponding products **4i-4m** in excellent yields, which could be further applied in traditional cross-coupling reactions. The presence of a variety of electron-donating/withdrawing groups in benzylamine moieties at either (*o/m/p*) position does not affect the efficiency of the process. However, steric hindrance was observed with 2-methoxy benzylamine, in which case trace amount of product **4n** was observed. The present catalytic system is also applicable to hetero and aliphatic amines under typical conditions, to afford the desired products **4o-4x** in moderate to excellent yield. However, with 2-picolyamine no desired product formation was observed. Interestingly, when reaction was performed with amino acid derivatives like ethyl glycinate (**5a**) and **1a** under standard condition, (Scheme 2) 53% of 1-tert-butyl 3-ethyl imidazo[1,5-a]pyridine-1,3-dicarboxylate (**6a**) was isolated. This method is useful for straight forward synthesis of functionalized imidazo [1, 5-a] pyridines. Under the same conditions secondary amines like dibenzyl amine and *n*-methyl benzyl amines were not proceeded efficiently (Scheme 2).

Then, to ascertain the reaction mechanism, some control experiments were performed (Scheme 3). Reaction of **1a** with *p*-toluidine **8a** under optimised conditions, we isolated 89% of imine product **9a** (eqn. 1) and with α-methyl benzyl amines **8b**, a different product **10a** was isolated (eqn. 2). Initially nitrogen of benzylamine forms C- N bond with pyridyl carbon, the presence of methyl

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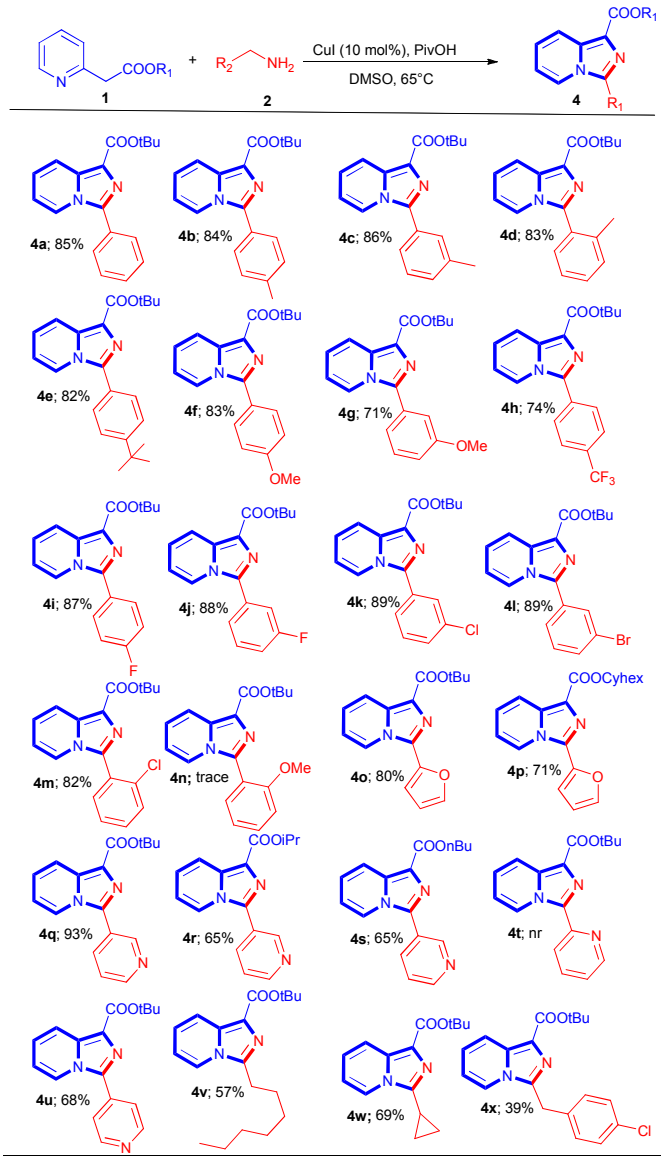
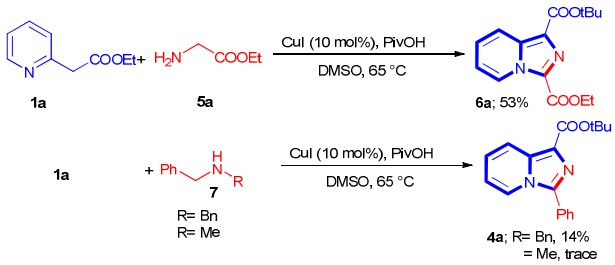
Table 3. Substrate Scope of various amines [a]

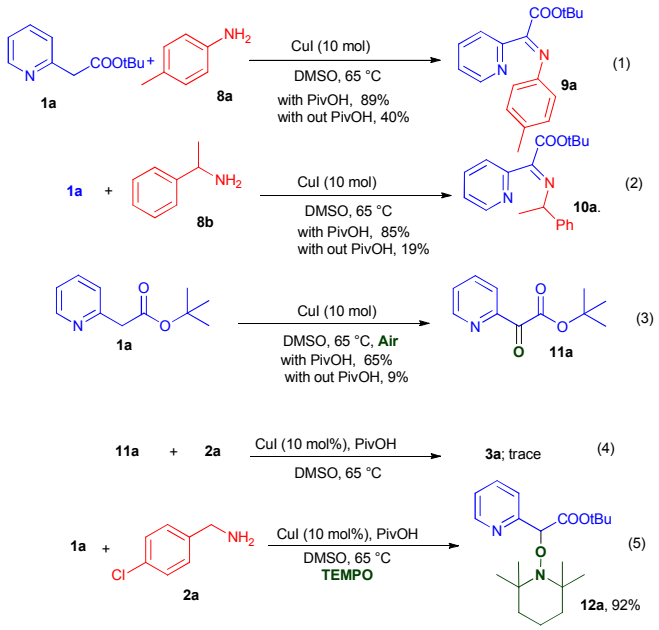


[a]Reaction conditions: **1** (0.25 mmol), **2** (0.5 mmol), additive (0.25 mmol), catalyst (0.025 mmol), solvent (1 mL), in an oil bath under open air, isolated yield, and nr: no reaction



Scheme 2.

group at α- position of benzylamine prevented the cyclization; hence formation product **10a** was obtained (eqn. 2). When the reaction of **1a** was subjected to these conditions without amine, the oxidised product *tert*-butyl 2-oxo-2-(pyridin-2-yl)acetate **11a** was isolated (eqn. 3). To understand the role of PivOH, we performed reactions of equations 1-3 without PivOH, in all the cases considerably low yield of products (**9a**,**10a** and **11a**) were observed. Based on these experiments, it indicates that, PivOH plays a crucial role to generate imine intermediate under the present conditions. Further by subjecting **11a** under the optimised conditions with **2a**, trace amount of product formation was observed (eqn. 4). To confirm the reaction whether ionic or radical pathway, **1a** and **2a** were subjected to the optimized conditions using TEMPO as radical scavenger (eqn. 5), as expected no desired product formation was observed, instead an adduct **12a** was isolated in 92 % yield, it indicates the radical reaction mechanism (Scheme 3).



Scheme 3. Additional reactions

Based on the above control experiments and literature reports,[6c&19] we proposed a plausible reaction mechanism as described in Scheme 4. Initially CuI coordinates either with pyridines or amines to form $L_nCu(I)$ complex, which is oxidized to Cu(II) species by O_2.[6a&20] The reaction of **1** with Cu(II) generates a radical intermediate **A**, which generates benzylic carbocation **B** via a single-electron-transfer process in the presence of Cu(II).[21] Addition of benzylic amine to **B** gives intermediate **C**, it further undergoes oxidation to provide imine intermediate **D**, which is further confirmed by the additional experiments (Scheme 3). Subsequently D further undergoes single-electron-transfer process (intermediates **E-G**) in the presence of Cu(II) catalyst.[6a&21] Attacking nitrogen lone pair of electrons from G, leads to cyclic intermediate H. Finally, aromatization of H will give the desired product (3 or 4).

In conclusion, we demonstrated a copper-catalyzed aerobic oxidative amination of C (sp3)-H bonds for the syntheses of imidazo [1, 5-a] pyridine-1-carboxylates under mild conditions. The method has the following advantages: i) use of atmospheric air as efficient and selective oxidant (oxygen source), ii) employing commercially available starting substrates and catalyst, iii) broad range of substrate scope with good to excellent yields, iv) activation of C(sp3)-H bonds under mild reaction temperature (65 °C).

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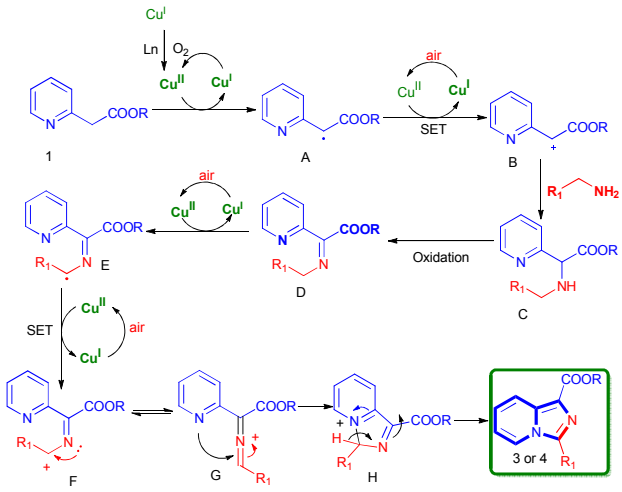

Scheme 4. Plausible mechanism

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Notes and references

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^{1}H and ^{13}C NMR spectra for all compounds and HRMS spectra for new compounds. Crystallographic data for compound **3a** (CCDC-1017738) can be obtained free of charge from the Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif. Electronic Supplementary Information (ESI) available: [details of any supplementary information available should be included here]. See DOI: 10.1039/c000000x.

1 (a) T. A. Ramirez, B. Zhao, and Y. Shi. *Chem. Soc. Rev.,* 2012, **41**, 931; (b) J. Ke, C. He, H. Liu, M. Li, and A. Lei *Chem. Commun.,* 2013, **49**, 7549; (c) W. Dong, L. Wang, K. Parthasarathy, F. Pan, and C. Bolm, *Angew. Chem. Int. Ed.* 2013, **52**, 11573; (d) J. Li, L. and Neuville. *Org. Lett.,* 2013, **15**, 175; (e) H. Chen, S. Sanjaya, Y-F. Wang, and S. Chiba. *Org. Lett.,* 2013, **15**, 212; (f) Y. Yang, C. Xie, Y. Xie, and Y. Zhang. *Org. Lett.,* 2012, **14**, 957; (g) A. Armstrong, and J. C. Collins, *Angew. Chem. Int. Ed.* 2010, **49**, 2282; (h) S. Rakshit, F. W. Patureau, and F. Glorius. *J. Am. Chem. Soc.,* 2010, **132**, 9585; (i) F. Collet, R. H. Dodd, and P. Dauban, *Chem. Commun*., 2009, 5061. (j) H. M. L. Davies, and J. R. Manning, *Nature* 2008, **451**, 417; (k) H. M. L. Davies, and M. S. Long, *Angew. Chem. Int. Ed*., 2005, **44**, 3518.

2 (a) M-N. Zhao, Z-H. Ren, Y-Y. Wang, and Z.-H. Guan. *Org. Lett.,* 2014, **16**, 608; (b) Á. Iglesias, R. Álvarez, Á. R. de Lera, and K. Muñiz, *Angew. Chem. Int. Ed.,* 2012, **51**, 2225; (c) T. Xiang, Y. Li, L. Mao, Q. Zhang, and Q. Zhang, *Chem. Commun*., 2012, **48**, 2246; (d) X.-Y. Liu, P. Gao, Y.-W. Shen, and Y.-M. Liang, *Org. Lett.,* 2011, **13**, 4196; (e) K. Sun, Y. Li, T. Xiong, J. Zhang, and Q. Zhang, *J. Am. Chem. Soc*., 2011, **133**, 1694. (f) J. Pan, M. Su, and S. L. Buchwald, *Angew. Chem. Int. Ed.,* 2011, **50**, 8647.

3 (a) B. Li, N. Wang, Y. Liang, S. Xu, and B. Wang. *Org. Lett.,* 2013, **15**, 136; (b) L. Wang L. and Ackermann. *Org. Lett.,* 2013, **15**, 176; (c) H. Dong, R. T. Latka, and T. G. Driver, *Org. Lett.,* 2011, **13**, 2726; (d) D. Intrievi, M. Mariani, A. Caselli, F. Ragaini, and E. Gallo, *Chem. Eur. J.,* 2012, **18**, 10487; (e) W. Xiao, C.-Y. Zhou, C.-M. Che, *Chem. Commun.,* 2012, **48**, 5871. (f) W. Xiao, C.-Y. Zhou, C.-M. Che, *Chem. Commun.,* 2012, **48**, 5871

4 (a) X-L. Lian, Z-H. Ren, Y-Y. Wang, and Z-H. Guan., *Org. Lett.,* 2014, **16**, 3360; (b) J. Zheng, M. Zhang, L. Huang, X. Hu, W. Wu, H. Huang, and H. Jiang., *Chem. Commun*., 2014, **50**, 3609; (c) L. Zheng, and R. Hua. *J. Org. Chem.,* 2014, **79** 3930; (d) K.-H. Ng, Z. Zhou, and W.-Y. Yu, *Org. Lett.,* 2012, **14**, 272; (e) K. Takashi, D. Yamaguchi, and J. Ishihara, *Org. Lett.,* 2012, **14**, 1644; (f) S. Kang, J. Han, and E. S. Lee, *Org. Lett.,* 2012, **14**, 4184; (g) J. Ryun, K. Shin, S. Park, and S. Chang, *Angew. Chem. Int. Ed.,* 2012, **51**, 9904; (h) K. Sun, S. Liu, P. M. Bec, and T. G. Driver, *Angew. Chem. Int. Ed.,* 2011, **50**, 1702. (i) J. Du Bois, *Org. Process Res. Dev.,* 2011, **15**, 758.

5 (a) J. Huang, T. Mao, and Q. Zhu, *Eur. J. Org. Chem.,* 2014, 2878; (b) H. Xu, X. Qiao, S.Yang, Z. Shen, *J. Org. Chem.,* 2014, **79**, 4414; (c) A. M. Suess, M. Z. Ertem, C. J. Cramer, and S. S. Stahl, *J. Am. Chem. Soc.,* 2013, **135**, 9797; (d) X. Li, L. He, H. Chen, W. Wu, and H. Jiang, *J. Org. Chem.,* 2013, **78**, 3636; (e) D. Janreddy, V. Kavala, C.-W. Kuo, W.-C. Chen, C. Ramesh, T. Kotipalli, T.-S. Kuo, M.-L. Chen, C.-H. He, and C.-F. Yao, *Adv. Synth. Catal.,* 2013, **355**, 2918; (f) R. W. Evans, J. R. Zbieg, S. Zhu, W. Li, and D. W. C. MacMillan, *J. Am. Chem. Soc*. 2013, **135**, 16074; (g) Y.-F. Wang, H. Chen, X. Zhu, and S. Chiba, *J. Am. Chem. Soc.,* 2012, **134**, 11980; (h) S. Sanjaya, and S. Chiba, *Org. Lett.,* 2012, **14**, 5342; (i) T. M. U. Ton, C. Tejo, D. L. Y. Tiong, P. W. H. Chan, *J. Am. Chem. Soc.,* 2012, **134**, 7344. (j) H. Wang, Y. Yong, D. Liang, L. Liu, J. Zhang, and Q. Zhu, *Angew. Chem. Int. Ed.,* 2011, **50**, 5678; (k) R. T. Gephart, and T. H. Warren *Organometallics,* 2012, **31**, 7728.

6 (a) S. E. Allen, R. R. Walvoord, R. Padilla-Salinas, and M. C. Kozlowski, *Chem. Rev.,* 2013, **113**, 6234; (b) A. E. Wendlandt, A. M. Suess, and S. S. Stahl, *Angew. Chem. Int. Ed.,* 2011, **50**, 11062; (c) Z. Shi, C. Zhang, C. Tang, and N. Jiao, *Chem. Soc. Rev.,* 2012, 41, 3381; (d) M. S. Sigman, and D. R. Jensen, *Acc. Chem. Res.,* 2006, **39**, 221; (e) K. M. Gligorich, and M. S. Sigman, *Angew. Chem. Int. Ed.,* 2006, **45**, 6612; (f) T. Punniyamurthy, S. Velusamy, and J. Iqbal, *Chem. Rev.,* 2005, **105**, 2329.

7 (a) J. A. Joule, and K. Mills, Heterocyclic Chemistry, 4th ed.; Blackwell Science: Oxford, U. K., 2000; Chapter 25; (b) A. R. Katritzky, Comprehensive Heterocyclic Chemistry III; Elsevier: Oxford, U.K., 2008; Vol. 11; (c) H. S. El Khadem, J. Kawai, and D. L. Swartz, *Carbohydr. Res*. 1989, **189**, 149; (d) D. A. Degoey C. A., Flentge, W. J. Flosi, D. J. Grampovnik, D. J. Kempf, L. L. Klein, M. C. Yeung, J. T. Randolph, X. C. Wang, and S. Yu, U.S. Pat. Appl. Publ. U.S. 2005148623;. *Chem. Abstr.* 2005, **143**, 133693; e) D. Kim, et al. *Bioorg. Med. Chem. Lett*., 2005, **15**, 2129.

8 (a) M. Nakatsuka, T. Shimamura, Jpn. Kokai Tokkyo Koho JP2001035664;. *Chem. Abstr.* 2001, **134**, 170632. (b) G. Tominaga, R.

Organic & Biomolecular Chemistry Accepted Manuscript

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Kohama, and A. Takano, Jpn. Kokai Tokkyo Koho JP2001006877; *Chem. Abstr.* 2001, **134**, 93136. c) D. Kitazawa, G. Tominaga, and A. Takano, Jpn. Kokai Tokkyo Koho JP 2001057292;. *Chem. Abstr.* 2001, **134**, 200276. d) L. Salassa, C. Garino, A. Albertino, G. Volpi, C. Nervi, R. Gobrtto, and K. I. Hardcastle, *Organometallics* 2008, **27**, 1427.

9 H. Nakamura, and H. Yamamoto, PCT Int. Appl. WO 2005043630. *Chem. Abstr*. 2005, **142**, 440277.

10 D. Kim, L. Wang, J. J. Hale, C. L. Lynch, R. J. Budhu, M. MacCoss, S. G. Mills, L. Malkowitz, S. L. Gould, J. A. DeMartino, M. S. Springer, D. Hazuda, M. Miller, J. Kessler, R. C. Hrin, G. Carver, A. Carella, K. Henry, J. Lineberger, W. A. Schleif, and E. A. Emini, *Bioorg. Med. Chem. Lett.* 2005, **15**, 2129.

11 (a) M. Alcarazo, S. J. Roseblade, A. R. Cowley, R. Fernan´dez, J. M. Brown, J. M. Lassaletta, *J. Am. Chem. Soc.,* 2005, **127**, 3290. (b) C. Burstein, C. W. Lehmann, and F. Glorius, *Tetrahedron* 2005, 61, 6207. (c) Hahn, F. E. *Angew. Chem., Int. Ed.,* 2006, **45**, 1348.

12 (a) T. Murai, E. Nagaya, K. Miyahara, F. Shibahara and T. Maruyama, *Chem. Lett.* 2013, **42**, 828. (b) A. M. Blanco-Rodriguez, H. Kvapilova, J. Sykora, M. Towrie, C. Nervi, G. Volpi, S. Zalis and A. Vlcek, J. *Am. Chem. Soc.* 2014, **136**, 5963. (c) M. Kriechbaum, D. Otte, M. List and U. Monkowius, *Dalton Trans.* 2014, **43**, 8781. (d) G. A. Ardizzoia, S. Brenna, S. Durini, B. Therrien and M. Veronelli, *Eur. J. Inorg. Chem.* 2014, 4310. (e) E. Y. Tsui and T. Agapie, *Polyhedron* 2014, **84**, 103.

13 (a) F. Shibahara, A. Kitagawa, E. Yamaguchi, and T. Murai, *Org. Lett*., 2006, 8, 5621. (b) V. S. Arvapalli, G. W. Chen, S. Kosarev, M. F. E. Tan, D. J. Xie , and L. Yet, *Tetrahedron Lett.,* 2010, **51**, 284. (c) M. Pineiro, E. Pinho, T. M. V. D. Melo, *Eur. J. Org. Chem*. 2009, 5287. d) J. Adrio, J. C. Carretero, *Chem. Commun*. 2011, **47**, 6784.

14 Y. Yan, Y. Zhang, Z. Zha, and Z. Wang, *Org. Lett.* 2013, **15**, 2274.

15 During the preparation of this manuscript, similar works are published (a) M. Li, Y. Xie, Y. Ye, Y. Zou. H. Jiang, and Wei Zeng, *Org. Lett.* 2014, **16**, 6232; (b). H. Wang, W. Xu, Z. Wang, L. Yu, and K. Xu, *J. Org. Chem.* 2015, DOI: 10.1021/jo5027723.

16. (a) A. R. Katritzky and G. Qiu *J. Org. Chem.,* 2001, **66** , 2862. (b) J. Wang, R. Mason, D. VanDerveer, K. Feng, and X. R. Bu. J. *Org. Chem.,* 2003, **68** 5415. (c) F. Shibahara, A. Kitagawa, E. Yamaguchi, and T. Murai, *Org. Lett.,* 2006, **8**, 5621. (d) F. Shibahara, R. Sugiura, E. Yamaguchi, A. Kitagawa and T Murai *J. Org. Chem.,* 2009, **74**, 3566. (e) J. T. Hutt and Z. D. Aron *Org. Lett.,* 2011, **13**, 5256. (f) Q. Wang, S. Zhang, F. Guo, B. Zhang, P. Hu, and Z. Wang, *J. Org. Chem.,* 2012, **77,** 11161. (g) G. Pelletier and A. B. Charette, *Org. Lett.,* 2013, **15**, 2290.

17 (a) K. C. Chunavala, G. Joshi, E. Suresh, and S. Adimurthy, *Synthesis*, 2011, *635*; (b) D. C. Mohan, S. N. Rao, and S. Adimurthy, *J. Org. Chem*. 2013, **78**, 1266; (c) D.C. Mohan, R. R. Donthiri, S. N. Rao, and S. Adimurthy, *Adv. Synth. Catal*. 2013, **355**, 2217; (d) D. C. Mohan, N. B. Sarang, and S. Adimurthy, *Tetrahedron Lett*, 2013, **54**, 6077; (e) D. C. Mohan, S. N. Rao, C Ravi, and S. Adimurthy, *Asian J. Org. Chem.* 2014, **3**, 609: (f) D. R. Reddy, P. Venkatanarayana, N.N.K. Reddy, D. Bairagi, and S. Adimurthy, *J. Org. Chem.* 2014, **79**, 11277; (g) D. C. Mohan, C Ravi, S. N. Rao, and S. Adimurthy, *Org. Biomol. Chem.,* 2015, DOI: 10.1039/C5OB00018A.

18 R. D. Patil, and S. Adimurthy, *Adv. Synth. Catal.* 2011, **353**, 1695.

19 (a) J. E. M. N. Klein , A. Perry , D. S. Pugh, and R. J. K. T. Zhang, *Org. Lett.,* 2010, **12**, 3446; (b) F-F. Wang, C-P. Luo, G. Denga, and L.Yang, *Green Chem.,* 2014, **16**, 2428; (c) W. Zhu, D. Zhang, N. Yanga, and H. Liu. *Chem. Commun.,* 2014, **10**. 1039; (d) C. Xu, L. Zhang, and S. Luo. *Angew. Chem. Int. Ed.* 2014, **53**, 4149.

20 (a) F. Shibahara, A. Suenami, A. Yoshida, and T. Murai, *Chem. Commun*. 2007, 2354. (b) S. Fukuzumi, L. Tahsini, Y. M. Lee, K. Ohkubo, W. Nam, and K. D. Karlin, *J. Am. Chem. Soc*. 2012, **134**, 7025. (c) D.Das, Y. M. Lee, K. Ohkubo, W. Nam, K. D. Karlin, and S. Fukuzumi, *J. Am. Chem. Soc*. 2013, **135**, 2825.

21 (a) N. Zhou, T. Xie, L. Liu, and Z. Xie. *J. Org. Chem*. 2014, **79**, 6061; (b) Y. Su, X. Sun, G. Wu, and N. Jiao. *Angew. Chem. Int. Ed*. 2013, **52**, 9808; (c) R. Yan, X. Liu, C. Pan, X. Zhou, X. Li, X. Kang, and G. Huang. *Org. Lett.,* 2013, **15**, 4876; (d) Bluhm, M. E.; Ciesielski, M.; Görls, H.; and Döring, M. *Angew. Chem., Int. Ed.* 2002, 41, 2962.

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