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Iron-Catalyzed Selective *N*-Methylation and *N*-Formylation of Amines with CO_2

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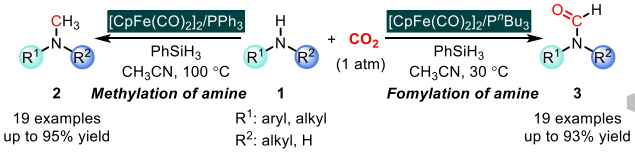
Abstract. We herein describe an efficient iron-catalyzed selective *N*-methylation and *N*-formylation of amines with CO_2 and silane using mono-phosphine as ligand. With commercially available $[CpFe(CO)_2]_2$ as catalyst, Fe-catalyzed methylation of amines was achieved with triphenylphosphine as a ligand. Using tributylphosphine as a ligand, Fe-catalyzed formylation of amines was realized at a lower temperature. The method was successfully applied in the late-stage methylation and formylation of drug molecules containing amine moiety.

Keywords: Iron; Mono-phosphine; Carbon dioxide; *N*-methylation; *N*-formylation

Carbon dioxide (CO_2) is an abundant, nontoxic, and renewable carbon feedstock, which has been widely used as a C1 building block for the production of fine chemicals.[1] In this respect, conversion of CO_2 into valuable products has gained continuing interest, especially with non-precious transition metal catalysis. With its high natural abundance, low cost and biological toxicity, and the ability to easily transfer one or two electrons to a substrate, iron is an ideal metal catalyst for CO_2 transformations.[2] With iron as catalyst, CO_2 has been successfully reduced into formic acid, formate, methanol, and so on.[3] Hydrogen gas is the cleanest reductant in the reduction of CO_2, however, harsh conditions are usually needed, such as high reaction temperature and high pressure of mixed gases. Because of their easy operation and tunable reactivity, hydrosilanes are attractive reagents in the reductive functionalization of CO_2.[4] In the past decade, catalytic *N*-methylation or *N*-formylation of amines with CO_2 and silanes has been achieved affording valuable methylamines[5-6] or formamides[7-8]. However, there are limited reports of the efficient catalytic system for the selective methylation and formylation of amines with CO_2 and silanes.

In 2014, Cantat and co-workers reported the first example of selective *N*-methylation and *N*-formylation of amines with CO_2 and silanes.[9] Their $Fe(acac)_2$/tetraphos system was found highly efficient for *N*-formylation of a variety of amines, but showed moderate selectivity for *N*-methylation of amines (3 examples of *N*-methylanilines). Later, several organocatalysts, Cs_2CO_3,[10] Betaine,[11] Glycine Betaine,[12] DBU,[13] and Guanidine,[14] were found efficient for selective *N*-methylation and *N*-formylation of amines. Recently, He and co-workers described efficient selective *N*-methylation and *N*-formylation of amines using CO_2 pressure-switched tungstate catalysis and ligand-controlled copper catalysis.[15] Meanwhile, Huang and colleagues described a Ni-catalyzed selective *N*-methylation and *N*-formylation of amines by turning CO_2 pressure and reaction temperature.[16] Continuing the interest in the reductive functionalization of CO_2,[13, 17] we wish to report here an Fe-catalyzed selective *N*-methylation and *N*-formylation of amines with CO_2 (Scheme 1). Excellent results have been achieved with commercially available $[CpFe(CO)_2]_2$ as catalyst, via choosing different mono-phosphine ligands and reaction temperatures.



Scheme 1. Fe-catalyzed Selective *N*-Methylation and *N*-Formylation of Amines with CO_2.

At the beginning, we chose commercially available *N*-ethylaniline **1a** as a model substrate to investigate the selective *N*-methylation and *N*-formylation reaction. After extensive screening, *N*-methylation product **2a** was obtained in excellent yield with $[CpFe(CO)_2]_2$ as catalyst, PPh_3 as ligand, $PhSiH_3$ as

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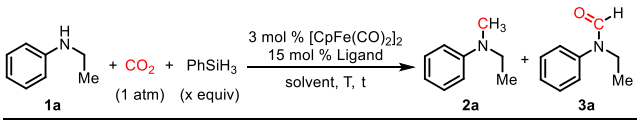
reductant in CH_3CN at 100 °C (Table 1, entry 1). The same result was obtained with PCy_3 or $P(^nBu)_3$ as ligand (Table 1, entries 2 and 3). Cost-effective and air-stable PPh_3 was chosen as the optimal ligand. Reducing the amount of $PhSiH_3$ to 3.0 equivalent led to **2a** in 95% yield (Table 1, entry 4). No reaction occurred when switching CH_3CN to THF (Table 1, entry 5). Control experiments demonstrated that the iron catalyst and the phosphine ligand are both necessary for the reaction (Table 1, entries 6 and 7). When decreasing the reaction temperature to 80 °C, the reaction ran smoothly in a slightly reduced yield, but the yield of *N*-formylation product **3a** increased obviously (Table 1, entry 8). Further lower the reaction temperature to 30 °C, product **3a** was obtained in 76% yield with 1.0 equivalent of $PhSiH_3$, together with 20% yield of **2a** (Table 1, entry 9). Ligand evaluation showed that best result was obtained with $P(^nBu)_3$ as ligand (Table 1, entries 10-11). A slightly lower yield was obtained with THF as solvent (Table 1, entry 12). The same as *N*-methylation reaction, no reaction occurred without iron catalyst or phosphine ligand (Table 1, entries 13 and 14).

Table 1. Fe-catalyzed Selective *N*-Methylation and *N*-Formylation of Amines with CO_2[a]

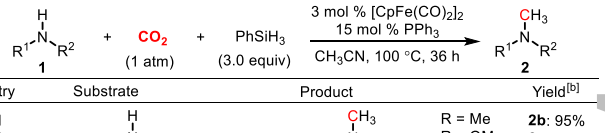


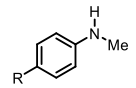
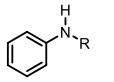
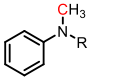
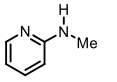
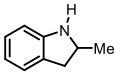
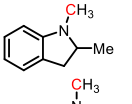
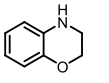
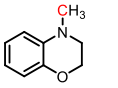
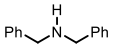
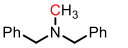
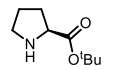
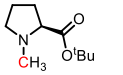
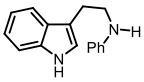
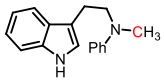
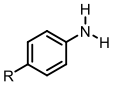
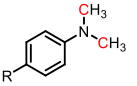
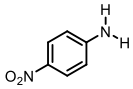
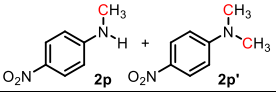
Entry	Ligand	$PhSiH_3$ (x equiv)	Solvent	T (°C) /t (h)	Yield of **2a** (%)[b]	Yield of **3a** (%)[b]
1	PPh_3	4.0	CH_3CN	100/36	95	0
2	PCy_3	4.0	CH_3CN	100/36	95	0
3	$P(^nBu)_3$	4.0	CH_3CN	100/36	95	0
4[c]	**PPh_3**	**3.0**	**CH_3CN**	**100/36**	**95 (92)**	**2**
5	PPh_3	3.0	THF	100/36	0	0
6[d]	PPh_3	3.0	CH_3CN	100/36	0	0
7	-	3.0	CH_3CN	100/36	0	0
8	PPh_3	3.0	CH_3CN	80/36	85	9
9	PPh_3	1.0	CH_3CN	30/24	20	76
10	PCy_3	1.0	CH_3CN	30/24	12	84
11[c]	**$P(^nBu)_3$**	**1.0**	**CH_3CN**	**30/24**	**6**	**92 (90)**
12	$P(^nBu)_3$	1.0	THF	30/24	4	87
13[d]	$P(^nBu)_3$	1.0	CH_3CN	30/24	0	0
14	-	1.0	CH_3CN	30/24	0	0

[a] All reactions were run with 0.2 mmol of **1a** in 1 mL solvent unless otherwise noted.
[b] The yield was determined by GC with *n*-dodecane as internal standard.
[c] Isolated yield in the parenthesis.
[d] Without Fe catalyst.

With the optimal reaction conditions in hand, we firstly evaluated the scope of the *N*-methylation of amines with CO_2 and $PhSiH_3$ (Table 2). Both electron-donating (4-Me, 4-MeO) and electron-withdrawing (4-Cl, 4-CO_2Me) groups on the aryl ring of aniline were well tolerated, affording the corresponding products **2b-e** in 73-95% yields (Table 2, entries 1-4). The *N*-alkyl substituent on the secondary monoaromatic amines could be removable allyl and sterically bulky cyclohexyl group (**2f** and **2g**). Moderate yield was obtained with heteroaryl-substituted amine (**2h**). Excellent yields were obtained with cyclic aryl amines, such as 2-methylindoline and benzomorpholine (**2i** and **2j**). The reaction also occurred smoothly with dibenzyl amine, giving the methylation product **2k** in moderate yield. The desired product **2m** were obtained in moderate yield with tryptamine derivative as substrate. Furthermore, primary aromatic amines were investigated under standard conditions. Dimethylated product **2n** and **2o** was obtained in good yield with aniline and 4-methoxyaniline as substrate, respectively (Table 1, entries 13 and 14). When 4-nitroaniline was used as substrate, mono-methylated product **4p** was obtained as the major product (Table 1, entry 15).

Table 2. Scope of the Fe/PPh_3-Catalyzed *N*-Methylation of Amines with CO_2[a]



Entry	Substrate	Product		Yield[b]
1			R = Me	**2b**: 95%
2			R = OMe	**2c**: 95%
3			R = Cl	**2d**: 84%
4			R = CO_2Me	**2e**: 73%
5			R = allyl	**2f**: 86%
6			R = Cy	**2g**: 88%
7				**2h**: 64%
8				**2i**: 85%
9				**2j**: 92%
10				**2k**: 60%
11				**2l**: trace
12				**2m**: 40%
13			R = H	**2n**: 92%
14			R = MeO	**2o**: 83%
15				**2p**: 80% **2p'**: 20%

[a] All reactions were carried out with 0.2 mmol of **1** in CH_3CN (1 mL) unless otherwise noted.
[b] isolated yields were provided.

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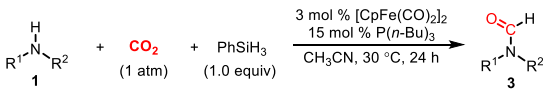
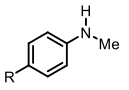
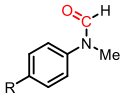
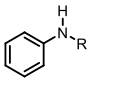
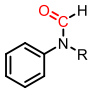
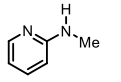
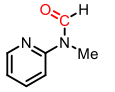
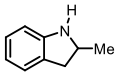
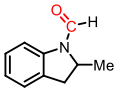
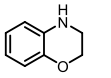
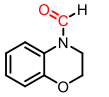
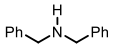
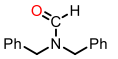
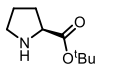
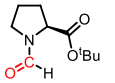
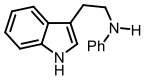
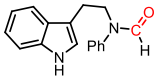
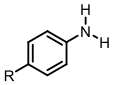
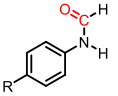
We next investigate the scope of the *N*-formylation of amines with CO_2 and $PhSiH_3$, as shown in Table 3. Formamides were obtained in 88-93% yields with *N*-methyl arylamines bearing electron-donating group (Me, OMe) and halogen atom (Cl) on the aryl ring of amines (Table 3, entries 1-3). However, slow reaction was observed and moderate yield was obtained with substrate bearing electron-withdrawing group on the *para* position of aniline (**3e**) and heteroarylamine (**3h**). High yields were obtaind with different *N*-alkyl substituted secondary monoaromatic amines, such as *N*-allyl group (**3f**) and *N*-cyclohexyl group (**3g**). Good results were also obtained with cyclic aryl amines (**3i** and **3j**). Notably, the reaction occurred smoothly with aliphatic amines giving the corresponding formylation products in good yields (**3k** and **3l**). Formylation of aniline and 4-methoxyaniline afforded **3n** and **3o** in good yields (Table 3, entries 13 and 14). However, trace amount of product **3p** was obtained with 4-nitroaniline as substrate (Table 3, entry 15).

Table 3. Scope of the Fe/P(^{n}Bu)$_3$-Catalyzed *N*-Formylation of Amines with CO_2[a]

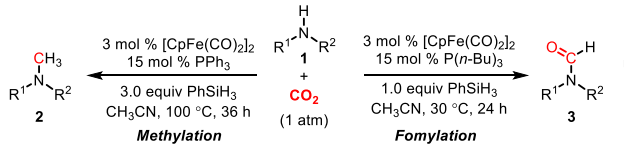


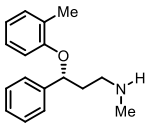
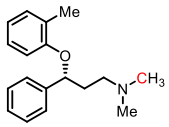
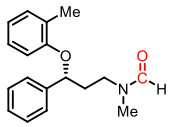
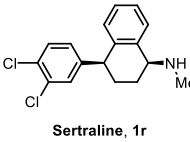
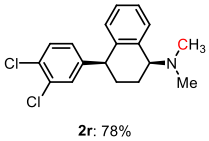
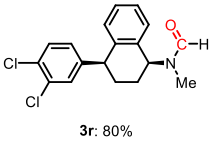
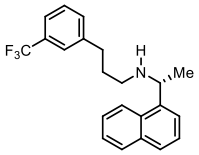
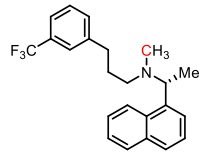
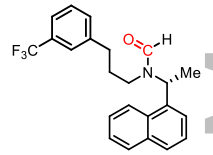
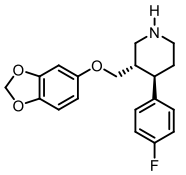
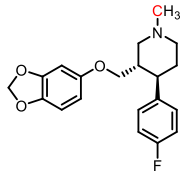
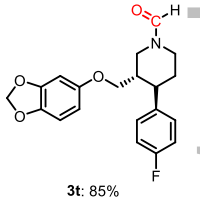
Entry	Substrate	Product		Yield[b]
1			R = Me	**3b**: 93%
2			R = OMe	**3c**: 93%
3			R = Cl	**3d**: 88%
4			R = CO_2Me	**3e**: 50% (40%)[c]
5			R = allyl	**3f**: 81%
6			R = Cy	**3g**: 80%
7				**3h**: 50% (35%)[c]
8				**3i**: 83%
9				**3j**: 85%
10				**3k**: 70%
11				**3l**: 70%
12				**3m**: 75%
13			R = H	**3n**: 88%
14			R = OMe	**3o**: 75%
15			R = NO_2	**3p**: trace

[a] All reactions were carried out with 0.2 mmol of **1** in CH_3CN (1 mL) unless otherwise noted.
[b] The isolated yields were provided.
[c] The yield of recovered starting material was given in the parenthesis.

Furthermore, we evaluated the current methods in the late-stage functionalization of biologically active pharmaceuticals (Table 4). Fe-catalyzed methylation of drugs molecules, Atomoxetine (**1q**), Sertraline (**1r**), Cinacalcet (**1s**), and Paroxetine (**1t**) was successfully achieved producing the desired products in moderate to good yields (**2q-t**). Undoubtedly, formylation of these drug molecules smoothly afforded the corresponding formamides in 70-85% yields (**3q-t**).

Table 4. Fe-Catalyzed *N*-Methylation and *N*-Formylation of drug molecules with CO_2[a]

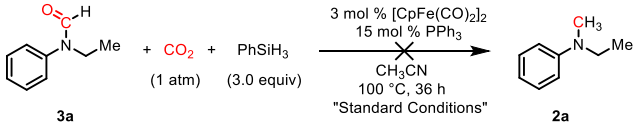


drug molecule, **1**	Product, **2**	Product, **3**
 **Atomoxetine**, **1q**	 **2q**: 50% (40%)[b,c]	 **3q**: 70%
 **Sertraline**, **1r**	 **2r**: 78%	 **3r**: 80%
 **Cinacalcet**, **1s**	 **2s**: 70%	 **3s**: 77%
 **Paroxetine**, **1t**	 **2t**: 30% (50%)[b,c]	 **3t**: 85%

[a] All reactions were carried out with 0.2 mmol of **1** in CH_3CN (1 mL) unless otherwise noted, and the isolated yields were provided.
[b] The yield of recovered starting material was given in the parenthesis.
[c] With toluene as the solvent.

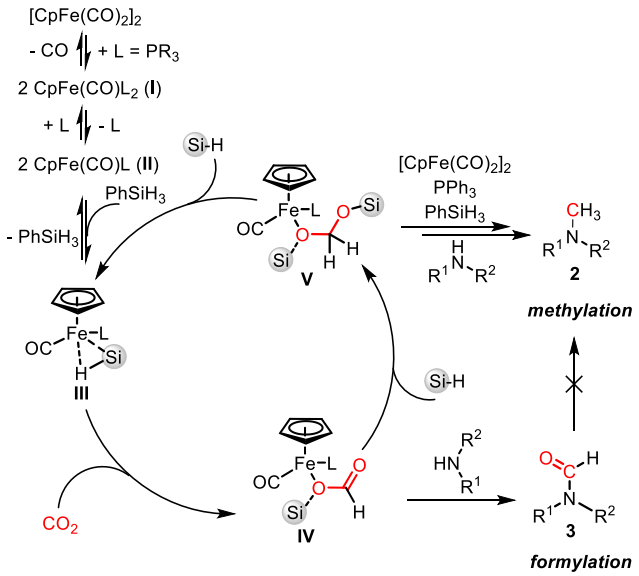
In the reductive fixation of CO_2 onto *N*-ethylaniline **1a**, *N*-methylated product **2a** was obtained as a major product at higher temperature, whereas *N*-formylation product **3a** was obtained as a major product at lower temperature. we proposed that formamide may be an intermediate in the *N*-methylation of amines. However, control experiment showed that **3a** could not be converted into the methylated product **2a** under the standard methylation conditions, indicating that *N*-formylation

product was not the intermediate to *N*-methylated product (Scheme 2).



Scheme 2. Control Experiment.

Based on our results and previous mechanistic studies on the reductive fixation of CO_2 onto amines,[18] the possible reaction pathway is described in Scheme 3. Tyler has reported that 19-electron Iron species **I** is easily generated by replacing a CO with two monophosphine ligand at iron of $[CpFe(CO)_2]_2$.[19] Disassociation of a phosphine ligand may lead to a 17-electron species **II**. The species **II** can also be obtained by ligand exchange of monophosphine with CO from $[CpFe(CO)_2]_2$.[20] In the presence of $PhSiH_3$, species **II** may be converted to η^2-silane complex **III**.[21] Successively, insertion of Fe-hydride into CO_2 generates intermediate **IV**.[22] Formamides **3** would be obtained by reaction of **IV** with amine via nucleophilic addition and elimination of silanol. At ahigh temperature, the intermediate **IV** would be reduced easily to methylene species **V**.[23] Unfortunately, the detection or isolation of intermediate **IV** and **V** in our system was unsuccessful. Reaction of amines with **V** gives *N*-methylated amines **2** as the final product through possible aminal intermediate.



Scheme 3. Plausible Reaction Pathways.

In summary, we have developed a Fe-catalyzed selective *N*-methylation and *N*-formylation for the synthesis of methylamines and formamides under mild condition with CO_2 as a sustainable C1 source. This catalytic system features high efficiency and good substrate scope using commercially available iron catalyst and mono-phosphine ligands. Further investigation of the reaction mechanism and expansion of the reductive C−C bond formation with CO_2 are ongoing in our laboratory.

Experimental Section

General procedure A for the Fe/PPh_3-catalyzed *N*-methylation of amines with CO_2 and $PhSiH_3$: An oven-dried Schlenk tube (25 mL) was charged with the substrate **1** (0.20 mmol, 1.0 equiv) and $[CpFe(CO)_2]_2$ (2.2 mg, 0.006 mmol, 0.03 equiv). The tube was then evacuated and back-filled with carbon dioxide for 3 times. PPh_3 (7.9 mg, 0.03 mmol, 0.15 equiv), $PhSiH_3$ (0.6 mmol, 75 μL, 3.0 equiv) and anhydrous acetonitrile (1.0 mL) were added via syringe under CO_2. Then the Schlenk tube was sealed at atmospheric pressure of CO_2 (1 atm) and the resulting mixture was stirred for 36 h at 100 °C. The mixture was cooled to room temperature and concentrated under reduced pressure. The residue was purified by column chromatography (petroleum ether/EtOAc 100/0~1/1 to DCM/MeOH 50/1~20/1) to give the pure desired product **2**.

General procedure B for the Fe/P(^{n}Bu)$_3$-catalyzed *N*-formylation of amines with CO_2 and $PhSiH_3$: An oven-dried Schlenk tube (25 mL) was charged with the substrate **1** (0.20 mmol, 1.0 equiv) and $[CpFe(CO)_2]_2$ (2.2 mg, 0.006 mmol, 0.03 equiv). The tube was then evacuated and back-filled with carbon dioxide for 3 times. P(*n*-Bu)$_3$ (7.5 μL, 0.03 mmol, 0.15 equiv), $PhSiH_3$ (0.2 mmol, 25 μL, 1.0 equiv) and anhydrous acetonitrile (1.0 mL) were added via syringe under CO_2. Then the Schlenk tube was sealed at atmospheric pressure of CO_2 (1 atm) and the resulting mixture was stirred for 24 h at 30 °C. The mixture was cooled to room temperature and concentrated under reduced pressure. The residue was purified by column chromatography (petroleum ether/EtOAc 100/0~1/1 to DCM/MeOH 100/1~ 20/1) to give the pure desired product **3**.

Acknowledgements

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References

[1] a) T. Sakakura, J.-C. Choi, H. Yasuda, *Chem. Rev.* **2007**, *107*, 2365; b) M. Cokoja, C. Bruckmeier, B. Rieger, W. A. Herrmann, F. E. Kuhn, *Angew. Chem.* **2011**, *123*, 8662; *Angew. Chem. Int. Ed.* **2011**, *50*, 8510; c) J. L. White, M. F. Baruch, J. E. Pander, Y. Hu, I. C. Fortmeyer, J. E. Park, T. Zhang, K. Liao, J. Gu, Y. Yan, T. W. Shaw, E. Abelev, A. B. Bocarsly, *Chem. Rev.* **2015**, *115*, 12888; d) Q. Liu, L. Wu, R. Jackstell, M. Beller, *Nat. Commun.* **2015**, *6*, 5933; e) J. Klankermayer, S. Wesselbaum, K. Beydoun, W.

Leitner, *Angew. Chem.* **2016**, *128*, 7416; *Angew. Chem. Int. Ed.* **2016**, *55*, 7296.

[2] a) B. Plietker, *Iron Catalysis in Organic Chemistry*, Wiley-VCH, Weinheim, **2008**; b) C. Bolm, J. Legros, J. Le Paih, L. Zani, *Chem. Rev.* **2004**, *104*, 6217; c) B. D. Sherry, A. Fürstner, *Acc. Chem. Res.* **2008**, *41*, 1500; d) K. Gopalaiah, *Chem. Rev.* **2013**, *113*, 3248; e) I. Bauer, H. J. Knolker, *Chem. Rev.* **2015**, *115*, 3170; f) A. Fürstner, *ACS Cent. Sci.* **2016**, *2*, 778; g) Elwira Bisz, M. Szostak, *ChemSusChem* **2017**, *10*, 3964; h) R. Shang, L. Ilies, E. Nakamura, *Chem. Rev.* **2017**, *117*, 9086; i) A. Piontek, E. Bisz, M. Szostak, *Angew. Chem.* **2018**, *130*, 11284; *Angew. Chem. Int. Ed.* **2018**, *57*, 11116.

[3] a) C. Federsel, A. Boddien, R. Jackstell, R. Jennerjahn, P. J. Dyson, R. Scopelliti, G. Laurenczy, M. Beller, *Angew. Chem.* **2010**, *122*, 9971*; Angew. Chem. Int. Ed.* **2010**, *49*, 9777; b) R. Langer, Y. Diskin-Posner, G. Leitus, L. J. W. Shimon, Y. Ben-David, D. Milstein, *Angew. Chem.* **2011**, *123*, 10122; *Angew. Chem. Int. Ed.* **2011**, *50*, 9948; c) J. L. Drake, C. M. Manna, J. A. Byers, *Organometallics* **2013**, *32*, 6891; d) C. E. Roth, A. Dibenedetto, M. Aresta, *Eur. J. Inorg. Chem.* **2015**, *2015*, 5066; e) X. Yang, *Chem. Commun.* **2015**, *51*, 13098; f) Y. Zhang, A. D. MacIntosh, J. L. Wong, E. A. Bielinski, P. G. Williard, B. Q. Mercado, N. Hazari, W. H. Bernskoetter, *Chem. Sci.* **2015**, *6*, 4291; g) H. Fong, J. C. Peters, *Inorg. Chem.* **2015**, *54*, 5124; h) F. Zhu, L. Zhu-Ge, G. Yang, S. Zhou, *ChemSusChem* **2015**, *8*, 609; i) F. Bertini, N. Gorgas, B. Stoger, M. Peruzzini, L. F. Veiros, K. Kirchner, L. Gonsalvi, *ACS Catal.* **2016**, *6*, 2889.

[4] Fow reviews: a) A. Tlili, E. Blondiaux, X. Frogneux, T. Cantat, *Green Chem.* **2015**, *17*, 157; b) Y. Li, X. Cui, K. Dong, K. Junge, M. Beller, *ACS Catal.* **2017**, *7*, 1077; c) R. A. Pramudita, K. Motokura, *Green Chem.* **2018**, *20*, 4834; d) J. R. Cabrero-Antonino, R. Adam Ortiz, M. Beller, *Angew. Chem.* **2018**; *Angew. Chem., Int. Ed.* **2018**. DOI:10.1002/anie.201810121; d) W. Wang, C. Xia, L. Wu, *Green Chem.* **2018**, *20*, 5415.

[5] Selected examples of metal-free methylation of amines with CO_2 and silane: a) S. Das, F. D. Bobbink, G. Laurenczy, P. J. Dyson, *Angew. Chem.* **2014**, *126*, 13090; *Angew. Chem. Int. Ed.* **2014**, *53*, 12876; b) Z. Yang, B. Yu, H. Zhang, Y. Zhao, G. Ji, Z. Ma, X. Gao, Z. Liu, *Green Chem.* **2015**, *17*, 4189; c) Y. Lu, Z. H. Gao, X. Y. Chen, J. Guo, Z. Liu, Y. Dang, S. Ye, Z. X. Wang, *Chem. Sci.* **2017**, *8*, 7637; d) H. Niu, L. Lu, R. Shi, C.-W. Chiang, A. Lei, *Chem. Commun.* **2017**, *53*, 1148; e) X.-F. Liu, C. Qiao, X.-Y. Li, L.-N. He, *Green Chem.* **2017**, *19*, 1726.

[6] Selected examples of transition-metal-catalyzed methylation of amines with CO_2 and silane: a) O. Jacquet, X. Frogneux, C. Das Neves Gomes, T. Cantat, *Chem. Sci.* **2013**, *4*, 2127; b) Y. Li, X. Fang, K. Junge, M. Beller, *Angew. Chem.* **2013**, *125*, 9747; *Angew. Chem., Int. Ed.* **2013**, *52*, 9568; c) L. González-Sebastián, M. Flores-Alamo, J. J. García, *Organometallics* **2015**, *34*, 763; d) O. Santoro, F. Lazreg, Y. Minenkov, L. Cavallo, C. S. J. Cazin, *Dalton Trans.* **2015**, *44*, 18138; e) Z. Yang, B. Yu, H. Zhang, Y. Zhao, Y. Chen, Z. Ma, G. Ji, X. Gao, B. Han, Z. Liu, *ACS Catal.* **2016**, *6*, 1268; f) T. V. Q. Nguyen, W.-J. Yoo, S. Kobayashi, *Adv. Synth. Catal.* **2016**, *358*, 452.

[7] Selected examples of metal-free formylation of amines with CO_2 and silane: a) C. Das Neves Gomes, O. Jacquet, C. Villiers, P. Thuery, M. Ephritikhine, T. Cantat, *Angew. Chem.* **2012**, *124*, 191; *Angew. Chem. Int. Ed.* **2012**, *51*, 187. b) O. Jacquet, C. Das Neves Gomes, M. Ephritikhine, T. Cantat, *J. Am. Chem. Soc.* **2012**, *134*, 2934. c) L. Hao, Y. Zhao, B. Yu, Z. Yang, H. Zhang, B. Han, X. Gao, Z. Liu, *ACS Catal.* **2015**, *5*, 4989; d) C. C. Chong, R. Kinjo, *Angew. Chem.* **2015**, *127*, 12284; *Angew. Chem. Int. Ed.* **2015**, *54*, 12116; e) L. Hao, Y. Zhao, B. Yu, Z. Yang, H. Zhang, B. Han, X. Gao, Z. Liu, *ACS Catal.* **2015**, *5*, 4989; f) B. Dong, L. Wang, S. Zhao, R. Ge, X. Song, Y. Wang, Y. Gao, *Chem. Commun.* **2016**, *52*, 7082; g) J. Song, B. Zhou, H. Liu, C. Xie, Q. Meng, Z. Zhang, B. Han, *Green Chem.* **2016**, *18*, 3956; h) H. Lv, Q. Xing, C. Yue, Z. Lei, F. Li, *Chem. Commun.* **2016**, *52*, 6545.

[8] Selected examples of transition-metal-catalyzed formylation of amines with CO_2 and silane: a) a) T. V. Q. Nguyen, W.-J. Yoo, S. Kobayashi, *Angew. Chem.* **2015**, *127*, 9341; *Angew. Chem., Int. Ed.* **2015**, *54*, 9209; b) Z.-Z. Yang, B. Yu, H. Zhang, Y. Zhao, G. Ji, Z. Liu, *RSC Adv.* **2015**, *5*, 19613; c) K. Motokura, N. Takahashi, A. Miyaji, Y. Sakamoto, S. Yamaguchi, T. Baba, *Tetrahedron* **2014**, *70*, 6951; d) S. Zhang, Q. Mei, H. Liu, H. Liu, Z. Zhang, B. Han, *RSC Adv.* **2016**, *6*, 32370; e) R. Luo, X. Lin, Y. Chen, W. Zhang, X. Zhou, H. Ji, *ChemSusChem* **2017**, *10*, 1224.

[9] X. Frogneux, O. Jacquet, T. Cantat, *Catal. Sci. Technol.* **2014**, *4*, 1529.

[10] C. Fang, C. Lu, M. Liu, Y. Zhu, Y. Fu, B.-L. Lin, *ACS Catal.* **2016**, *6*, 7876;

[11] X.-F. Liu, X.-Y. Li, C. Qiao, H.-C. Fu, L.-N. He, *Angew. Chem.* **2017**, *129*, 7533; *Angew. Chem., Int. Ed.* **2017**, *56*, 7425.

[12] C. Xie, J. Song, H. Wu, B. Zhou, C. Wu, B. Han, *ACS Sustainable Chem. Eng.* **2017**, *5*, 7086.

[13] G. Li, J. Chen, D.-Y. Zhu, Y. Chen, J.-B. Xia, *Adv. Synth. Catal.* **2018**, *360*, 2364.

[14] R. L. Nicholls, J. A. McManus, C. M. Rayner, J. A. Morales-Serna, A. J. P. White, B. N. Nguyen, *ACS Catal.* **2018**, *8*, 3678.

[15] a) W catalyst: M.-Y. Wang, N. Wang, X.-F. Liu, C. Qiao, L.-N. He, *Green Chem.* **2018**, *20*, 1564; b) Cu catalyst: X.-D. Li, S.-M. Xia, K.-H. Chen, X.-F. Liu, H.-R. Li, L.-N. He, *Green Chem.* **2018**, *20*, 4853.

[16] H. Li, T. P. Gonçalves, Q. Zhao, D. Gong, Z. Lai, Z. Wang, J. Zheng, K.-W. Huang, *Chem. Commun.* **2018**, *54*, 11395.

[17] a) D.-Y. Zhu, L. Fang, H. Han, Y.-Z. Wang, J.-B. Xia, *Org. Lett.* **2017**, *19*, 4259; b) D.-Y. Zhu, W.-D. Li, C. Yang, J. Chen, J.-B. Xia, *Org. Lett.* **2018**, *20*, 3282.

[18] a) F. Huang, G. Lu, L. Zhao, H. Li, Z.-X. Wang, *J. Am. Chem. Soc.* **2010**, *132*, 12388; b) Q. Zhou, Y. Li, *J. Am. Chem. Soc.* **2015**, *137*, 10182; c) C. Zhang, Y. Lu, R. Zhao, W. Menberu, J. Guo, Z. X. Wang, *Chem. Commun.*, **2018**, *54*, 10870.

[19] A. S. Goldman, D. R. Tyler, *Inorg. Chem.* **1987**, *26*, 253.

[20] T. A. Shackleton, S. C. Mackie, S. B. Fergusson, L. J. Johnston, M. C. Baird, *Organometallics* **1990**, *9*, 2248.

[21] E. Scharrer, S. Chang, M. Brookhart, *Organometallics* **1990**, *14*, 5686.

[22] a) X. Yang, *ACS Catal.* **2011**, *1*, 849; b) L. Yang, H. Wang, N. Zhang, S. Hong, *Dalton Trans.* **2013**, *42*, 11186; c) H. Fong, J. C. Peters, *Inorg. Chem.* **2015**, *54*, 5124.

[23] G. Jin, C. G. Werncke, Y. Escudie, S. Sabo-Etienne, S. Bontemps, *J. Am. Chem. Soc.* **2015**, *137*, 9563.

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Iron-Catalyzed Selective *N*-Methylation and *N*-Formylation of Amines with CO_2

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Wen-Duo Li, Dao-Yong Zhu, Gang Li, Jie Chen and Ji-Bao Xia*