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Article

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From Internal Olefins to Linear Amines: Ruthenium-Catalyzed Domino Water-Gas Shift/Hydroaminomethylation Sequence

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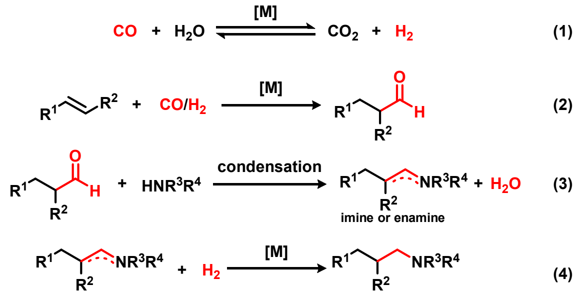
ABSTRACT: A selective ruthenium-catalyzed water-gas shift/hydroformylation of internal olefins and olefin mixtures is reported. This novel domino reaction takes place through a catalytic water-gas shift reaction, subsequent olefin isomerization, followed by hydroformylation and reductive amination. Key to the success for the efficient one-pot process is the use of a specific 2-phosphino-substituted imidazole ligand and triruthenium dodecacarbonyl as pre-catalyst. Industrially important internal olefins react with various amines to give the corresponding tertiary amines generally in good yield and selectivity. This reaction sequence constitutes an economically attractive and environmentally favorable process for the synthesis of linear amines.

KEYWORDS: internal olefin, linear amine, ruthenium, water-gas shift, hydroaminomethylation, domino reaction.

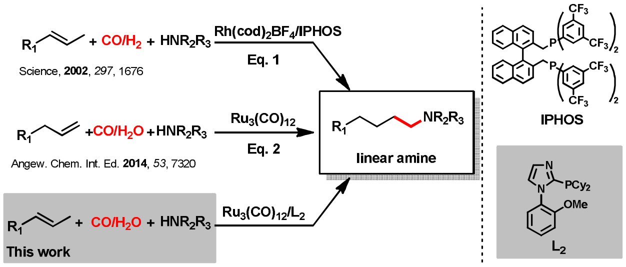
INTRODUCTION

Aliphatic amines are produced as valuable intermediates in the bulk and fine chemical industries.[1] They are used as agrochemicals, pharmaceutical intermediates, solvents, dyes, monomers for polymerization and functional materials.[2] Nowadays, methods such as reductive amination of carbonyl compounds,[3] amination of alcohols,[4] and hydrogenation of the respective nitriles,[5] prevail in industry. In addition, a plethora of less atom-efficient methodologies such as classical nucleophilic substitution of alkyl halides[3a] and cross coupling reactions,[6] or less general methods like hydroamination of alkenes,[3a, 7] are continuously being investigated for laboratory scale synthesis. Despite all these known processes, there is still considerable interest to develop improved routes to this class of compounds. An environmentally benign synthesis of amines from olefins is the so-called hydroaminomethylation reaction.[8] This domino sequence includes hydroformylation of olefins to aldehydes, followed by condensation with amine to imines or enamines and final hydrogenation gives the desired alkylated amines (Scheme 1, (2) to (4)). A number of protocols for hydroaminomethylation of terminal olefins have been disclosed in recent years,[9] however, more challenging is the synthesis of linear amines from internal olefins. Such reactions are of industrial relevance because mixtures of internal olefins such as butenes, hexenes and octenes are more cost-efficient than the corresponding terminal olefins. Thus, our group developed the first general catalyst system for linear amine synthesis from internal olefins in 2002 (Scheme 2, Eq. 1).[10] This work was inspired by related hydroformylations of internal olefins to give linear products.[11]



Scheme 1. Domino water-gas shift / hydroaminomethylation sequence. (1) Metal catalyzed water gas shift reaction. (2) Hydroformylation of olefins. (3) Condensation of aldehyde and amine. (4) Hydrogenation of imine or enamine.

Interestingly, most of the known hydroformylation reactions of internal olefins require relatively expensive rhodium/ligand catalyst systems to ensure high activity and selectivity in the carbonylation step.[12] Hence, it is highly desirable to apply less costly alternative metals to realize this process.[13] In this regard, it is noteworthy that recently the groups of Nozaki,[14] Krische,[15] Ding,[16] Ackermann[17], Sanford[18] and others[19] as well as ourselves[20] have reported ruthenium-catalyzed C-C and C-hetero bond formation reactions and demonstrated their potential and application to hydroformylation reactions. Moreover, in 1970s, homogeneous ruthenium,[21] as well as rhodium[22] and platinum[23] catalysts were found to demonstrate good activity for water gas shift reaction (Scheme 1, (1)), then these catalytic systems were further applied to hydrofomylation and hydrogenation reactions.[24] In this context, our group firstly presented hydrogen-free ruthenium-catalyzed hydroaminomethylation of terminal olefins in 2014 (Scheme 2, Eq. 2).[25] Although high yields and regioselectivities were obtained with terminal olefins, unfortunately, internal olefins showed only low activity in this reaction. These results intrigued us to develop a more general, practical and complementary ruthenium-catalyzed hydroaminomethylation of industrial importantly internal olefins.



Scheme 2. Hydroaminomethylation of olefins for the synthesis of linear amines. Eq. 1, rhodium catalyzed hydroaminomethylation of internal olefins. Eq. 2, ruthenium catalyzed water-gas shift/hydroaminomethylation of terminal olefins.

In order to produce linear amines from internal olefins via hydroaminomethylation, a suitable catalytic system should fulfil several requirements: (1) This domino sequence consists of water-gas shift reaction, olefin isomerization, hydroformylation, condensation and final hydrogenation (Scheme 1) and the catalyst system should be compatible with all these steps; (2) to selectively produce linear amines, the hydroformylation of the terminal olefin must occur much faster and with high regioselectivity compared with the reaction of the internal olefin; (3) the catalyst must be active, selective for the hydrogenation step of imine or enamine under CO pressure.

Based on our continuing interest in hydroformylation using so-called “alternative metal” catalysts, recently we showed the catalytic activity of ruthenium catalysts in the presence of 2-phosphino-substituted imidazole ligands in hydroformylation and hydroaminomethylation reactions.[26] These results inspired us to apply such catalytic systems for the selective water-gas shift/hydroaminomethylation of internal olefins.

RESULTS AND DISCUSSION

At the start of this project, we evaluated the effect of different ligands using 2-octene **1a** and piperidine **2a** as model substrates (Figure 1). In the absence of any ligand, only 13% yield of the desired 1-nonyl piperidine **3a** was obtained with a low regioselectivity. Using PPh_3 or PCy_3 as ligands did not improve the activity or selectivity. However, in the presence of L_1 (2-(dicyclohexylphosphanyl)-1-phenyl-1H-imidazole) a high yield of **3a** (93%) and good regioselectivity (*n*/*i* = 86:14) was observed. To elaborate the influence of this ligand structure on the catalyst reactivity, more heterocyclic and aromatic phosphine ligands were employed (L_2 to L_{10}). To our delight, applying L_2 (2-(dicyclohexylphosphanyl)-1-(2-methoxyphenyl)-1H-imidazole) as the most efficient ligand and afforded **3a** in 95% yield and good regioselectivity (*n*/*i* = 87:13). Notably, L_3 with a less basic phenyl substituent on the phosphorus suppressed this reaction. L_4 bearing the ^{i}Pr group on phosphorus also provided good regioselectivity albeit gave slightly lower yield. Other imidazole ligands, such as L_5 and L_6, displayed high yields, while with moderate regioselectivities were observed. Benzimidazole-type ligand L_6 did not present any improvement in this reaction. Changing the imidazolyl moiety to pyrrol, pyrazol, and aromatic type ligands (L_8-L_{10}), the catalytic performance was declined. These results demonstrate that a hemilabile behaviour[27] between the imine nitrogen of the imidazolyl unit and the ruthenium center may play an important role in this catalytic transformation.[28]

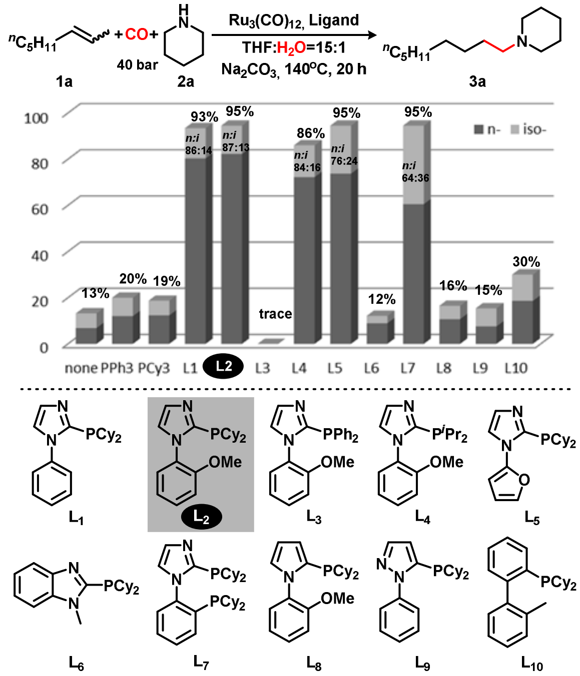
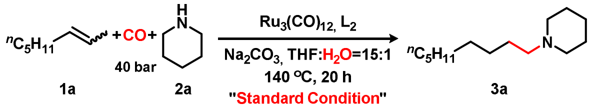


Figure 1. Ligand effects for the water-gas shift / hydroaminomethylation sequence of 2-octene with piperidine. Reaction conditions: **1a** (1.3 mmol), **2a** (1.0 mmol), $Ru_3(CO)_{12}$ (0.5 mol%), monodentate ligand (1.5 mol%), bidentate ligand (0.75 mol%), Na_2CO_3 (5.0 mol%), CO (40 bar), THF (1.5 mL), H2O (0.1 mL), 140 °C, 20 h. Yields and selectivity were determined by GC analysis using isooctane as the internal standard.

Then, we investigated the effects of other reaction parameters for the benchmark reaction, and the results are summarized in Table 1. When $Ru_3(CO)_{12}$ was replaced by $Fe_3(CO)_{12}$, essentially no reaction occurred (entry 2). Control experiments showed that the ruthenium catalyst and water are essential for this reaction (entries 3 and 4). Decreasing the temperature to 120°C led to significantly slower conversion, affording only 9% yield of **3a** (entry 5). As to the solvent, toluene also gave good regioselectivity albeit lower yield was obtained (entry 6), while dipolar aprotic NMP showed less efficiency in terms of chemical yield (entry 7). Notably, the reaction without base demonstrated lower yield, but still significant activity (entry 8). Addition of benzoic acid instead of Na_2CO_3 led to no improvement for this transformation (entry 9).

Table 1. Domino water-gas shift/hydroaminomethylation of 2-octene **1a** with piperidine **2a**: Effects of reaction parameters. [a]

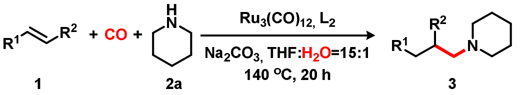


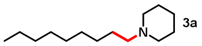
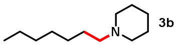
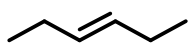
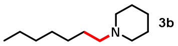
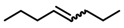
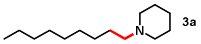
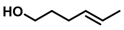
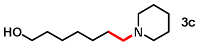
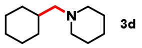
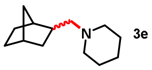
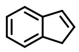
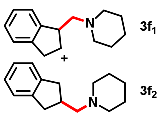
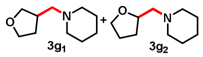
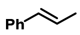
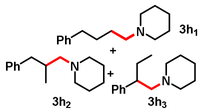
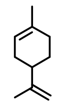
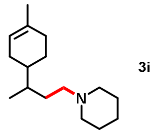
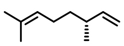
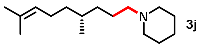
Entry	Variation from "Standard Condition"	Yield [%]	n:i
1	None	95	87:13
2	$Fe_3(CO)_{12}$ instead of $Ru_3(CO)_{12}$	0	-
3	Without $Ru_3(CO)_{12}$	0	-
4	Without water	0	-
5	120 °C instead of 140 °C	9	87:13
6	Toluene instead of THF	65	87:13
7	NMP instead of THF	33	85:15
8	Without Na_2CO_3	71	87:13
9	Benzoic acid instead of Na_2CO_3	73	87:13

Standard reaction conditions: [a] **1a** (1.3 mmol), **2a** (1.0 mmol), $Ru_3(CO)_{12}$ (0.5 mol%), L_2 (1.5 mol%), Na_2CO_3 (5.0 mol%), CO (40 bar), THF (1.5 mL), H_2O (0.1 mL), 140 °C, 20 h. Yield and selectivity were determined by GC analysis.

With the optimized reaction conditions in hand, we explored the substrate scope. At first, the reactions of various internal olefins **1** with piperidine **2a** were studied. We were pleased to find that related internal olefins (2-hexene, 3-hexene) reacted well to give the corresponding linear amines in good yield and regioselectivity (Table 2, entries 1-3). On the other hand, 4-octene gave only 22% yield with moderate regioselectivity (Table 2, entry 4). Functionalized 4-hexen-1-ol also reacted smoothly with a good yield (77%) and high regioselectivity (*n:i* = 91:9) (Table 2, entry 5). Interestingly, cyclic olefins including cyclohexene, norbornene, and indene were found to be suitable substrates to afford the corresponding amines in high yields (Table 2, entries 6-8). 2,3-Dihydrofuran, which represents an enol ether substrate, provided a good yield but poor regioselectivity (Table 2, entry 9). With (1*E*)-1-propenylbenzene, a mixture of three different amines was obtained (Table 2, entry 10). When limonene and (–)-β-citronellene were used as the substrates, the internal bond remained intact and only the double bond in the terminal positions were selectively hydroformylated to the corresponding amines with moderate to good results (Table 2, entries 11-12).

Table 2. Variation of different internal olefins for the synthesis of amines.[a]

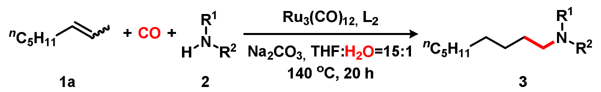


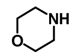
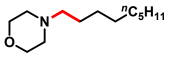
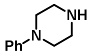
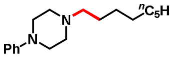
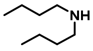
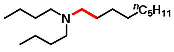
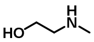
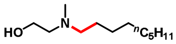
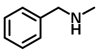
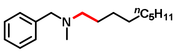
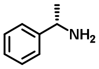
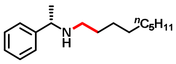
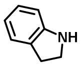
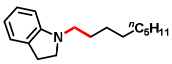
Entry	Olefin	Major product	Yield [%]	n:i
1		 3a	94	87:13
2		 3b	85	89:11
3		 3b	72^b	80:20
4		 3a	22^b	65:35
5	HO 	 3c	77	91:9
6		 3d	85	-
7		 3e	78	-
8		 $3f_1$ + $3f_2$	81	$3f_1$:$3f_2$ 87:13
9		 $3g_1$ + $3g_2$	71	$3g_1$:$3g_2$ 59:41
10	Ph 	 $3h_1$ + $3h_2$ + $3h_3$	53	$3h_1$:$3h_2$:$3h_3$ 34:8:58
11		 3i	58	99:1
12		 3j	90	99:1

Reaction conditions: [a] **1** (1.3 mmol), **2a** (1.0 mmol), $Ru_3(CO)_{12}$ (0.5 mol%), L_2 (1.5 mol%), Na_2CO_3 (5.0 mol%), CO (40 bar), THF (1.5 mL), H_2O (0.1 mL), 140 °C, 20 h. Isolated yield. Selectivity was determined by GC analysis. [b] **1** (1.3 mmol), **2a** (1.0 mmol), $Ru_3(CO)_{12}$ (1.0 mol%), L_2 (3.0 mol%), Na_2CO_3 (5.0 mol%), CO (40 bar), THF (1.5 mL), H_2O (0.1 mL), 140 °C, 20 h. Yield and selectivity was determined by GC analysis.

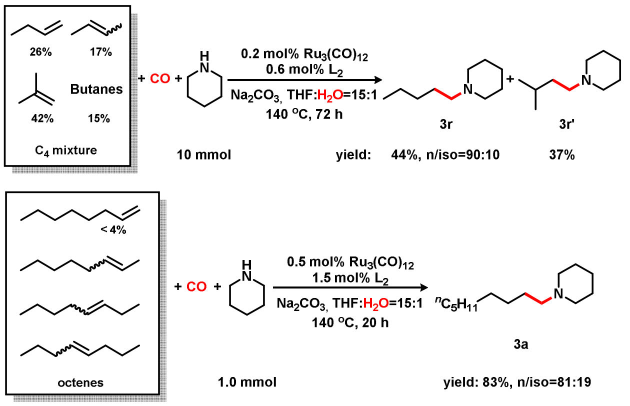
Furthermore, the reactivity of different amines was investigated using 2-octene as substrate (Table 3). With cyclic secondary amines like morpholine and 1-phenylpiperazine, good yields and regioselectivities were achieved (Table 3, entries 1 and 2). Acyclic amines such as di-n-butylamine, and (2-methylamino)ethanol also underwent this transformation smoothly in moderate and high yields and regioselectivities (Table 3, entries 3 and 4). Secondary benzylic amines were found to be suitable substrates, too; however product yields were only moderate (Table 3, entries 5-6). Finally, indoline was alkylated under the reaction conditions, albeit in low yield (Table 3, entry 7).

Table 3. Substrates scope for different amines. [a]



Entry	Amine	Major product	Yield [%]	*n:i*
1		 3k	65	85:15
2		 3l	65	84:16
3		 3m	87	86:14
4		 3n	77	75:25
5		 3o	63	84:16
6		 3p	35	85:15
7		 3q	18	86:164

Reaction conditions: [a] **1a** (1.3 mmol), **2** (1.0 mmol), $Ru_3(CO)_{12}$ (0.5 mol%), L_2 (1.5 mol%), Na_2CO_3 (5.0 mol%), CO (40 bar), THF (1.5 mL), H_2O (0.1 mL), 140 °C, 20 h. Isolated yield. Selectivity was determined by GC analysis.



Scheme 3. Synthetic applications by using crack C4 and a mixture of octenes. Reaction conditions: For crack C4 (0.72 g), **2a** (10 mmol), $Ru_3(CO)_{12}$ (0.2 mol%), L_2 (0.6 mol%), Na_2CO_3 (5.0 mol%), CO (50 bar), THF (15 mL), H_2O (1 mL), 140 °C, 72 h. Isolated yield. Selectivity was determined by GC analysis. For octenes (1.3 mmol), **2a** (1.0 mmol), $Ru_3(CO)_{12}$ (0.5 mol%), L_2 (1.5 mol%), Na_2CO_3 (5.0 mol%), CO (40 bar), THF (1.5 mL), H_2O (0.1 mL), 140 °C, 20 h. Isolated yield. Selectivity was determined by GC analysis.

Next, we were interested in demonstrating the utility of this method for the hydroaminomethylation of industrially important building blocks (Scheme 3). Here, crack C4, a mixture including 1-butene, 2-butenes, isobutene and butanes, which is a product from cracking of naphtha (light gasoline), reacted to the corresponding linear amines **3s** and **3s**' in high yield and regioselectivity with only 0.2 mol% $Ru_3(CO)_{12}$. Additionally, a mixture of octenes, which is mainly manufactured by oligomerization of ethylene, was also applied to this reaction and gave 81% yield of **3a** with a selectivity of *n:i*=81:19.

Finally, the reaction progress of this ruthenium-catalyzed water-gas shift/hydroformylation of 2-octene **1a** and piperidine **2a** was examined in more detail. As depicted in Figure 2a, the gas consumption started only after 2.5 hours and within this time only small amounts of E/Z isomerization of 2-octene were observed. Then, 2-octene **1a** was consumed slowly and at the same time, the corresponding amine **3a** and other internal octenes (3-octene and 4-octene) were formed (Figure 2b). It is noteworthy that 1-octene, which is proposed as the intermediate in this transformation, was not accumulated during the reaction. In agreement with our previous work,[26a, 26b] this result is attributed to the faster hydroformylation of terminal olefins. In addition, neither aldehyde, enamine nor imine were detected during the whole reaction time, which illustrates a fast process of the aldehyde with the amine and subsequent hydrogenation reaction.

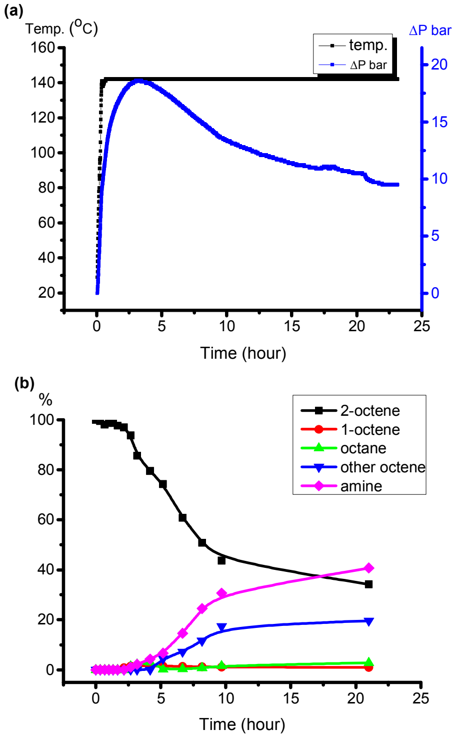


Figure 2. (a) Δp (Pressure change compared to initial pressure) curve and temperature curve. (b) Composition of the reaction mixture.

CONCLUSIONS

In summary, we have developed a novel domino sequence for the conversion of internal olefins to linear amines via catalytic water-gas shift reaction, subsequent olefin isomerization, followed by hydroformylation and reductive amination. Comparing with expensive rhodium catalyst, as a less costly alternative metal, ruthenium also demonstrates good reactivity and selectivity in this reaction. More importantly, in the presence of a special imidazole ligand, the corresponding linear amines are obtained in general in moderate to good yields and regioslectivity. Interestingly, the conversion of industrially available bulk mixtures of olefins such as crack C4 and octenes proceed in excellent yields considering the number of reaction steps. This procedure is expected to complement the current methods for hydroaminomethylation reactions in organic synthesis.

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Notes

The authors declare no competing financial interest.

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REFERENCES

1. Amines Market by Amine Type - Global Trends and Forecast to 2020. By: marketsandmarkets.com, December, 2015.

2. Lawrence, S. A., *Amines: Synthesis, Properties and Applications*. Cambridge University Press: Cambridge, 2006, November.

3. (a) Müller, T. E.; Beller, M., *Chem. Rev.* **1998**, *98*, 675-704; (b) Gross, T.; Seayad, A. M.; Ahmad, M.; Beller, M., *Org. Lett.* **2002**, *4*, 2055-2058; (c) Storer, R. I.; Carrera, D. E.; Ni, Y.; MacMillan, D. W. C., *J. Am. Chem. Soc.* **2006**, *128*, 84-86; (d) Ricci, A., *Modern Amination Methods*. Wiley-VCH: Weinheim, Germany, 2007; (e) Lee, O.-Y.; Law, K.-L.; Yang, D., *Org. Lett.* **2009**, *11*, 3302-3305.

4. (a) Trost, B., *Science* **1991**, *254*, 1471-1477; (b) Hamid, M. H. S. A.; Slatford, P. A.; Williams, J. M. J., *Adv. Synth. Catal.* **2007**, *349*, 1555-1575; (c) Dobereiner, G. E.; Crabtree, R. H., *Chem. Rev.* **2010**, *110*, 681-703; (d) Guillena, G.; J. Ramón, D.; Yus, M., *Chem. Rev.* **2010**, *110*, 1611-1641; (e) Watson, A. J. A.; Williams, J. M. J., *Science* **2010**, *329*, 635-636; (f) Bähn, S.; Imm, S.; Neubert, L.; Zhang, M.; Neumann, H.; Beller, M., *ChemCatChem* **2011**, *3*, 1853-1864; (g) Gunanathan, C.; Milstein, D., *Science* **2013**, *341*, 1229712.

5. (a) Nishimura, S., *Handbook of Heterogeneous Catalytic Hydrogenation for Organic Synthesis*. John Wiley & Sons: 2001; (b) Gomez, S.; Peters, J. A.; Maschmeyer, T., *Adv. Synth. Catal.* **2002**, *344*, 1037-1057; (c) Bini, L.; Müller, C.; Wilting, J.; von Chrzanowski, L.; Spek, A. L.; Vogt, D., *J. Am. Chem. Soc.* **2007**, *129*, 12622-12623; (d) Enthaler, S.; Addis, D.; Junge, K.; Erre, G.; Beller, M., *Chem.–Eur. J.* **2008**, *14*, 9491-9494; (e) Göthlich, A. P. V.; Tensfeldt, M.; Rothfuss, H.; Tauchert, M. E.; Haap, D.; Rominger, F.; Hofmann, P., *Organometallics* **2008**, *27*, 2189-2200; (f) Reguillo, R.; Grellier, M.; Vautravers, N.; Vendier, L.; Sabo-Etienne, S., *J. Am. Chem. Soc.* **2010**, *132*, 7854-7855; (g) Bornschein, C.; Werkmeister, S.; Wendt, B.; Jiao, H.; Alberico, E.; Baumann, W.; Junge, H.; Junge, K.; Beller, M., *Nat. Commun.* **2014**, *5*, 4111.

6. (a) Guram, A. S.; Rennels, R. A.; Buchwald, S. L., *Angew. Chem. Int. Ed.* **1995**, *34*, 1348-1350; (b) Wolfe, J. P.; Buchwald, S. L., *J. Org. Chem.* **1996**, *61*, 1133-1135; (c) Hartwig, J. F., *Angew. Chem. Int. Ed.* **1998**, *37*, 2046-2067; (d) Hartwig, J. F., *Acc. Chem. Res.* **1998**, *31*, 852-860; (e) Wolfe, J. P.; Wagaw, S.; Marcoux, J.-F.; Buchwald, S. L., *Acc. Chem. Res.* **1998**, *31*, 805-818; (f) Hartwig, J. F., *Nature* **2008**, 455, 314-322.

7. (a) Kaspar, L. T.; Fingerhut, B.; Ackermann, L., *Angew. Chem. Int. Ed.* **2005**, *44*, 5972-5974; (b) Müller, T. E.; Hultzsch, K. C.; Yus, M.; Foubelo, F.; Tada, M., *Chem. Rev.* **2008**, *108*, 3795-3892.

8. (a) Reppe, W.; Vetter, H., *Justus Liebigs Annalen der Chemie* **1953**, *582*, 133-161; (b) Laine, R. M., *J. Org. Chem.* **1980**, *45*, 3370-3372; (c) Eilbracht, P.; Bärfacker, L.; Buss, C.; Hollmann, C.; Kitsos-Rzychon, B. E.; Kranemann, C. L.; Rische, T.; Roggenbuck, R.; Schmidt, A., *Chem. Rev.* **1999**, *99*, 3329-3366; (d) Crozet, D.; Urrutigoïty, M.; Kalck, P., *ChemCatChem* **2011**, *3*, 1102-1118; (e) Raoufmoghaddam, S., *Org. Biomol. Chem.* **2014**, *12*, 7179-7193.

9. (a) Ahmed, M.; Seayad, A. M.; Jackstell, R.; Beller, M., *J. Am. Chem. Soc.* **2003**, *125*, 10311-10318; (b) Koç, F.; Wyszogrodzka, M.; Eilbracht, P.; Haag, R., *J. Org. Chem.* **2005**, *70*, 2021-2025; (c) Ahmed, M.; Buch, C.; Routaboul, L.; Jackstell, R.; Klein, H.; Spannenberg, A.; Beller, M., *Chem.–Eur. J.* **2007**, *13*, 1594-1601; (d) Vieira, T. O.; Alper, H., *Chem. Commun.* **2007**, 2710-2711; (e) Hamers, B.; Bäuerlein, P. S.; Müller, C.; Vogt, D., *Adv. Synth. Catal.* **2008**, *350*, 332-342; (f) Vieira, T. O.; Alper, H., *Org. Lett.* **2008**, *10*, 485-487; (g) Hamers, B.; Kosciusko-Morizet, E.; Müller, C.; Vogt, D., *ChemCatChem* **2009**, *1*, 103-106; (h) Subhani, M. A.; Müller, K.-S.; Eilbracht, P., *Adv. Synth. Catal.* **2009**, *351*, 2113-2123; (i) Kubiak, R.; Prochnow, I.; Doye, S., *Angew. Chem. Int. Ed.* **2010**, *49*, 2626-2629; (j) Liu, G.; Huang, K.; Cai, C.; Cao, B.; Chang, M.; Wu, W.; Zhang, X., *Chem.–Eur. J.* **2011**, *17*, 14559-14563; (k) Crozet, D.; Gual, A.; McKay, D.; Dinoi, C.; Godard, C.; Urrutigoïty, M.; Daran, J.-C.; Maron, L.; Claver, C.; Kalck, P., *Chem.–Eur. J.* **2012**, *18*, 7128-7140; (l) Dong, K.; Fang, X.; Jackstell, R.; Beller, M., *Chem. Commun.* **2015**, *51*, 5059-5062.

10. Seayad, A.; Ahmed, M.; Klein, H.; Jackstell, R.; Gross, T.; Beller, M., *Science* **2002**, *297*, 1676-1678.

11. (a) van der Veen, L. A.; Kamer, P. C. J.; van Leeuwen, P. W. N. M., *Angew. Chem. Int. Ed.* **1999**, *38*, 336-338; (b) Selent, D.; Wiese, K.-D.; Röttger, D.; Börner, A., *Angew. Chem. Int. Ed.* **2000**, *39*, 1639-1641; (c) Klein, H.; Jackstell, R.; Wiese, K.-D.; Borgmann, C.; Beller, M., *Angew. Chem. Int. Ed.* **2001**, *40*, 3408-3411; (d) Ahmed, M.; Bronger, R. P. J.; Jackstell, R.; Kamer, P. C. J.; van Leeuwen, P. W. N. M.; Beller, M., *Chem.–Eur. J.* **2006**, *12*, 8979-8988; (e) Liu, G.; Huang, K.; Cao, B.; Chang, M.; Li, S.; Yu, S.; Zhou, L.; Wu, W.; Zhang, X., *Org. Lett.* **2012**, *14*, 102-105.

12. (a) Van Leeuwen, P. W. N. M.; Claver, C., *Rhodium Catalyzed Hydroformylation*. Springer Netherlands: 2002; Vol. 22; (b) Franke, R.; Selent, D.; Börner, A., *Chem. Rev.* **2012**, *112*, 5675-5732.

13. Pospech, J.; Fleischer, I.; Franke, R.; Buchholz, S.; Beller, M., *Angew. Chem. Int. Ed.* **2013**, *52*, 2852-2872.

14. (a) Takahashi, K.; Yamashita, M.; Nozaki, K., *J. Am. Chem. Soc.* **2012**, *134*, 18746-18757; (b) Takahashi, K.; Yamashita, M.; Tanaka, Y.; Nozaki, K., *Angew. Chem. Int. Ed.* **2012**, *51*, 4383-4387.

15. (a) Zbieg, J. R.; Yamaguchi, E.; McInturff, E. L.; Krische, M. J., *Science* **2012**, *336*, 324-327; (b) Sam, B.; Breit, B.; Krische, M. J., *Angew. Chem. Int. Ed.* **2015**, *54*, 3267-3274.

16. (a) Han, Z.; Rong, L.; Wu, J.; Zhang, L.; Wang, Z.; Ding, K., *Angew. Chem. Int. Ed.* **2012**, *51*, 13041-13045; (b) Zhao, B.; Han, Z.; Ding, K., *Angew. Chem. Int. Ed.* **2013**, *52*, 4744-4788; (c) Zhang, L.; Han, Z.; Zhao, X.; Wang, Z.; Ding, K., *Angew. Chem. Int. Ed.* **2015**, *54*, 6186-6189.

17. (a) Ackermann, L.; Vicente, R.; Kapdi, A. R., *Angew. Chem. Int. Ed.* **2009**, *48*, 9792-9826; (b) Hofmann, N.; Ackermann, L., *J. Am. Chem. Soc.* **2013**, *135*, 5877-5884; (c) Ackermann, L., *Acc. Chem. Res.* **2014**, *47*, 281-295.

18. (a) Huff, C. A.; Sanford, M. S., *J. Am. Chem. Soc.* **2011**, *133*, 18122-18125; (b) Rezayee, N. M.; Huff, C. A.; Sanford, M. S., *J. Am. Chem. Soc.* **2015**, *137*, 1028-1031.

19. (a) Isnard, P.; Denise, B.; Sneeden, R. P. A.; Cognion, J. M.; Durual, P., *J. Organomet. Chem.* **1982**, *240*, 285-288; (b) Kondo, T.; Akazome, M.; Tsuji, Y.; Watanabe, Y., *J. Org. Chem.* **1990**, 55, 1286-1291; (c) Omura, S.; Fukuyama, T.; Horiguchi, J.; Murakami, Y.; Ryu, I., *J. Am. Chem. Soc.* **2008**, *130*, 14094-14095.

20. (a) Liu, Q.; Wu, L.; Fleischer, I.; Selent, D.; Franke, R.; Jackstell, R.; Beller, M., *Chem.–Eur. J.* **2014**, *20*, 6888-6894; (b) Pospech, J.; Tlili, A.; Spannenberg, A.; Neumann, H.; Beller, M., *Chem.–Eur. J.* **2014**, *20*, 3135-3141; (c) Wu, L.; Liu, Q.; Fleischer, I.; Jackstell, R.; Beller, M., *Nat. Commun.* **2014**, 5, 3091; (d) Wu, L.; Liu, Q.; Jackstell, R.; Beller, M., *Org. Chem. Front.* **2015**, *2*, 771-774.

21. (a) Laine, R. M.; Rinker, R. G.; Ford, P. C., *J. Am. Chem. Soc.* **1977**, *99*, 252-253; (b) King, R. B., *J. Organomet. Chem.* **1999**, *586*, 2-17.

22. Cheng, C.-H.; Hendriksen, D. E.; Eisenberg, R., *J. Am. Chem. Soc.* **1977**, *99*, 2791-2792.

23. Cheng, C.-H.; Eisenberg, R., *J. Am. Chem. Soc.* **1978**, *100*, 5968-5970.

24. (a) Kang, H. C.; Mauldin, C. H.; Cole, T.; Slegeir, W.; Cann, K.; Pettit, R., *J. Am. Chem. Soc.* **1977**, *99*, 8323-8325; (b) Okano, T.; Kobayashi, T.; Konishi, H.; Kiji, J., *Bull. Chem. Soc. Jpn.* **1981**, *54*, 3799-3805.

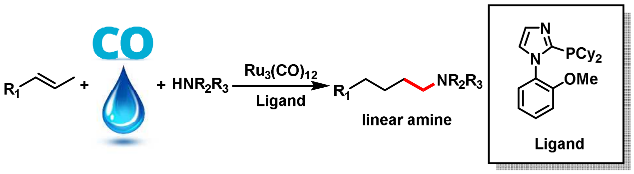
25. Gülak, S.; Wu, L.; Liu, Q.; Franke, R.; Jackstell, R.; Beller, M., *Angew. Chem. Int. Ed.* **2014**, *53*, 7320-7323.

26. (a) Wu, L.; Fleischer, I.; Jackstell, R.; Profir, I.; Franke, R.; Beller, M., *J. Am. Chem. Soc.* **2013**, *135*, 14306-14312; (b) Wu, L.; Fleischer, I.; Jackstell, R.; Beller, M., *J. Am. Chem. Soc.* **2013**, *135*, 3989-3996; (c) Fleischer, I.; Wu, L.; Profir, I.; Jackstell, R.; Franke, R.; Beller, M., *Chem.–Eur. J.* **2013**, *19*, 10589-10594; (d) Fleischer, I.; Dyballa, K. M.; Jennerjahn, R.; Jackstell, R.; Franke, R.; Spannenberg, A.; Beller, M., *Angew. Chem. Int. Ed.* **2013**, *52*, 2949-2953.

27. (a) Braunstein, P.; Naud, F., *Angew. Chem. Int. Ed.* **2001**, *40*, 680-699; (b) Grotjahn, D. B.; Gong, Y.; Zakharov, L.; Golen, J. A.; Rheingold, A. L., *J. Am. Chem. Soc.* **2006**, *128*, 438-453; (c) Díez, V.; Espino, G.; Jalón, F. A.; Manzano, B. R.; Pérez-Manrique, M., *J. Organomet. Chem.* **2007**, *692*, 1482-1495; (d) Grotjahn, D. B.; Zeng, X.; Cooksy, A. L.; Kassel, W. S.; DiPasquale, A. G.; Zakharov, L. N.; Rheingold, A. L., *Organometallics* **2007**, *26*, 3385-3402; (e) Grotjahn, D. B., *Dalton Transactions* **2008**, 6497-6508; (f) Hintermann, L.; Dang, T. T.; Labonne, A.; Kribber, T.; Xiao, L.; Naumov, P., *Chem.–Eur. J.* **2009**, *15*, 7167-7179; (g) Grotjahn, D. B., *Pure Appl. Chem.* **2010**, *82*, 635-647; (h) Kubis, C.; Profir, I.; Fleischer, I.; Baumann, W.; Selent, D.; Fischer, C.; Spannenberg, A.; Ludwig, R.; Hess, D.; Franke, R.; Börner, A., *Chem.–Eur. J.* **2015**, DOI: 10.1002/chem.201504051.

28. For some preliminary mechanistic studies for the interaction of this imidazole-type ligand and Ru center, please see Supporting Information, Scheme S1 to S3.

TOC


R1
+
CO
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Ru3(CO)12
Ligand
R1
NR2R3
linear amine
N
N
PCy2
OMe
Ligand