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Efficient and recyclable ionic diphosphine-based Ir-catalyst for hydroaminomethylation of olefins with H₂O as hydrogen source

Huan Liu,^a Da Yang,^a Dong-Liang Wang,^a Peng Wang,^a Yong Lu,^a Giang VO-Thanh,^b and Ye Liu^a*

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Hydroaminomethylation of olefins with H₂O as hydrogen source was accomplished over an Ir-catalyst with the involvement of an ionic diphosphine (L6). The use of H₂O as the hydrogen source could completely inhibit the hydrogenation of olefins. The π -accepting ability and improved stability of L6 rendered the corresponding Ir-catalyst high activity and good longevity for the cycling uses.

Amines and their derivatives were important compounds used as agrochemicals, pharmaceutical intermediates, solvents, dyes, monomers for polymerization, and functional materials¹. A number of reactions for the synthesis of amines have been extensively studied, such as hydroamination of olefins or alkynes^{2,3}, hydrogenation of the respective nitriles^{4,5}, amination of aryl halides^{6,7}, the *N*-alkylation with alcohols^{8,9} and the reductive amination with carbonyl compounds^{10,11}. Despite all these known processes, there are still considerable interests in developing high atom-economic synthesis routes to such compounds. Hydroaminomethylation^{12,13}, the one-pot tandem hydroformylation-reductive amination, is a high atomeconomic method for the synthesis of amines from olefins.

Since hydroaminomethylation discovered in 1949 by Reppe¹⁴, a number of transition metal catalysts, including complexes of rhodium^{15,16}, ruthenium¹⁷⁻¹⁹ and even Rh/Ir dual-metals^{20,21}, have been evaluated in this transformation. Anyway, the monometallic Ir-catalyze hydroaminomethylation has never been reported in the literature.

Herein we reported the first example of Ir-catalyzed hydroaminomethylation of olefins with the involvement of a novel ionic diphosphine (L6). However, Ir-complexes were

active catalysts for hydrogenation of olefins²² as well for hydrogenation of imines²³. In order to eliminate the undesired hydrogenation of olefins in the course of hydroaminomethylation, the required H₂ gas was generated in situ herein through water-gas shift reaction (WGSR, H₂O + CO \rightarrow H₂ + CO₂) over the Ir-catalyst^{24,25}. Compare to using H₂ gas, the use of water as hydrogen source is advantageous with safety, low-cost, and environmental friendliness. In this synthesis protocol, the hydroaminomethylation of olefins towards amines with H₂O as the hydrogen source is a one-pot four-step tandem reaction including (1) WGSR, (2) hydroformylation of olefins, (3) condensation of aldehydes and amines²⁶, and (4) hydrogenation of imines/iminiums (Scheme 1). In principle, there are three basic requirements for the Ircatalyst applied in this tandem transformation. (1) It should possess multiple catalytic functions which are compatible for each step; (2) It should be moisture-insensitive to allow the presence of water in the step of WGSR; (3) It should be stable enough to fulfill recyclability, which fits the merits of hydroaminomethylation as a high atom-economic process for the synthesis of amines from olefins.



^{a.}Shanghai Key Laboratory of Green Chemistry and Chemical Processes, School of Chemistry & Molecular Engineering, East China Normal University, Shanghai 200062, PR China.

^{b.} Institut de Chimie Moléculaire et des Matériaux d'Orsay, UMR 8182, Bat. 420, Université Paris-Sud 91405, Orsay Cedex, France

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Page 2 of 4

Journal Name

Firstly, the hydroaminomethylation of 1-hexene with Nmethylaniline was investigated as a model reaction. For this reaction, when H₂O was applied as hydrogen source, atom economy was calculated as high as 70% with CO₂ as the only released byproduct. Under the optimal conditions (140 °C, Ir/P=1/1, 4.0 MPa CO, and NMP as the solvent) (see S. Table 1 in ESI), the ligand effect on the catalytic performance of [Ir(COD)Cl]₂ was studied in Table 1, in which the neutral and the corresponding ionic mono-/di-phosphines were selected. It was found that the ionic phosphines universally led to the much higher yields of the targeted products in comparison to those over the neutral counterparts (Entry 2 vs 1; Entry 4 vs 3; Entry 6 vs 5). Specifically, over the ionic diphosphine of L6, the yield of N-heptyl-N-methylaniline reached 93% whereas its neutral counterpart of L5 just corresponded to 32% yield (Entry 6 vs 5). Anyway, the neutral phosphines without the electrostatic repulsive interaction all resulted in the much higher regioselectivities to the linear products (Entries 1, 3 and 5).

nethylaniline over different ligands ^a						
\mathcal{H}_3	Me +	[lr(COD)Cl] ₂ - Li CO/H ₂ O	igand H_3 lir	N Me near N-heptyl-N- methylaniline	+ () ₃ N M. branched N- methylar	e neptyl-N- nilline
		PF	Ph ₂ Me / OTf	n-Bu~N_N	n-Bu	-Me OTf
	L1	L2		L3	L4	
		Ph ₂ P N N h ₂ L5	Me	20Tr Ph ₂ P N N PPh ₂ L6	N ⁺	
Entry	Ligand	Conv. (%) ^b	Sel. (%) ^b Amine	Isomer	Hexane	L/B ^b
1	L1	32	>99	-	<1	88:12
2	L2	86	>99	-	<1	84:16
2 3	L2 L3	86 33	>99 >99	-	<1 <1	84:16 93:7
2 3 4	L2 L3 L4	86 33 85	>99 >99 >99	- -	<1 <1 <1	84:16 93:7 85:15
2 3 4 5	L2 L3 L4 L5	86 33 85 32	>99 >99 >99 >99	- - -	<1 <1 <1 <1	84:16 93:7 85:15 92:8
2 3 4 5 6	L2 L3 L4 L5 L6	86 33 85 32 93	>99 >99 >99 >99 >99	- - -	<1 <1 <1 <1 <1	84:16 93:7 85:15 92:8 84:16
2 3 4 5 6 7 ^c	L2 L3 L4 L5 L6 L6	86 33 85 32 93 92	>99 >99 >99 >99 >99 >99 81	-	<1 <1 <1 <1 <1 <1 <1 19	84:16 93:7 85:15 92:8 84:16 85:15
2 3 4 5 6 7 ^c 8 ^d	L2 L3 L4 L5 L6 L6 L6	86 33 85 32 93 92 99	>99 >99 >99 >99 >99 >99 81	- - - -	<1 <1 <1 <1 <1 <1 19 15	84:16 93:7 85:15 92:8 84:16 85:15 -
2 3 4 5 6 7 ^c 8 ^d 9	L2 L3 L4 L5 L6 L6 L6 PPh3	86 33 85 32 93 92 99 55	>99 >99 >99 >99 >99 81 - >99	-	<1 <1 <1 <1 <1 19 15 <1	84:16 93:7 85:15 92:8 84:16 85:15 - 87:13

 Table
 1
 Ir-catalyzed
 hydroaminomethylation
 of
 1-hexene
 with
 N-methylapiline
 over different ligands³

^a [Ir(COD)Cl]₂ 0.025 mmol (Ir 1.0 mol %), mono-phosphine 0.05 mmol, diphosphine 0.025 mmol (**L5** and **L6**), P/Ir = 1 (molar ratio), 1-hexene 5.0 mmol, *N*-methylaniline 8.0 mmol, *N*-methyl pyrrolidone (NMP) 2 mL (solvent), time 22 h, temperature 140 °C, H₂O 0.3 mL, CO 4.0 MPa; ^b Determined by GC; ^cCO/H₂ = 3/1 (4.0 MPa), time 8 h; ^d [Rh(COD)Cl]₂.

The magnitude of ${}^{1}J_{^{11}p_{e},^{77}se}$ in the ${}^{77}Se$ isotopomer of the corresponding phosphine-selenide in ${}^{31}P$ NMR spectra has been used to evaluate the π -acceptor ability of a phosphine 27,28 . An increase of ${}^{1}J_{^{11}p,^{27}se}$ indicates an increase in the character of π -acceptor ability (i.e., less σ -donor ability). The ${}^{31}P$ NMR spectra of the phosphine-selenides (Fig. 1) demonstrated that **L6**

possessed much stronger π -acceptor ability with $\frac{1}{\sqrt{2}}$ Hz than L5 (${}^{1}J_{\mu}{}^{77}s_{e}$ = 735 Hz). Reasonably, PPL6 based P catalyst, Ir-P bond was consolidated due to the intensive π -backdonation interaction between Ir-center and the electron-deficient ligand of L6. Accordingly, the consilidated Ir-P bond did weaken the Ir-CO bond and favor the dissociation of CO ligand to form the corresponding Ir-acyl complex. In addition, the TG/DTG analysis confirmed that the ionic phosphines generally possessed better stability against oxidative degradation than their neutral counterparts (see S. Fig. 1 in ESI). For example, in air flow, L6 decomposed ca. 280 °C whereas L5 at 120 °C. Consequently, L6based Ir-catalyst was oxygen-insensitive, which facilitated the process simplicity and manipulations in open air. These reasons could account for the better catalytic performance over L6-base Ir catalyst than that of L5-based one (Entry 6 vs 5). Although the mono-phopshines of L2 and L4 also possessed the similar π acceptor ability like L6 (Fig. 1: L2, ¹J³¹_P.⁷⁷_{Se} = 780 Hz; L4, ¹J³¹_P.⁷⁷_{Se} = 786 Hz), the favourable chelation of L6 to Ir-center as a diphosphine ligand with flexible butyl chain could protect Ir-catalyst against deactivation, resulting in its better performance (Entry 6 vs 2 and 4). Notably, the use of H₂O as the hydrogen source dramatically inhibited the hydrogenation of 1-hexene (Entries 1-6 vs 7).





Comparatively, when the syngas (4.0 MPa, $CO/H_2=3/1$ volume ratio) was applied under the same conditions, 17% yield of hexane was obtained due to the serious hydrogenation of 1-hexene (Entry 7). Surprisingly, over **L6**-based Rh-catalyst, the hydroaminomethylation completely stopped while the competitive side reactions such as polymerization and hydrogenation became predominant (Entry 8). By using PPh₃ or no ligand to repeat the reaction, the activities of Ir-catalyst decreased obviously along with the dropped conversions of 1-hexene (Entries 9 and 10).

The reaction evolution profiles of hydroaminomethylation of 1-hexene with *N*-methylaniline over **L6**-base Ir-catalyst (Fig. 2) indicated that, due to the relatively sluggish release of H_2

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COMMUNICATION

through WGSR, the hydroaminomethylation performed much slower than that in syngas (CO/H $_2$ 4.0 MPa). Therefore, the undesired hydrogenation of 1-hexene was completely depressed.



Fig. 2 The evolution profiles of 1-hexene conversion and product yield vs reaction time catalyzed by **L6**-based Ir-catalyst ([Ir(COD)Cl]₂ 0.025 mmol, **L6** 0.025 mmol, 1-hexene 5.0 mmol, *N*-methylaniline 8.0 mmol, NMP 2 mL, H₂O 0.3 mL, CO 4.0 MPa (or CO/H₂ 4.0 MPa, CO/H₂ =3/1 volume ratio), temperature 140 °C).

The remarkable performance of L6-based Ir-catalystriforothe efficient hydroaminomethylation evoked us to explore the formation and stability of the active Ir-H species, which was responsible for the key step of hydroformylation, via the high pressure in situ FT-IR spectroscopy ²⁹. The in situ FT-IR spectra were presented in Fig. 3 and Fig. 4. In syngas atmosphere, besides the strong characteristic vibrations of gaseous CO at 2180 and 2115 cm⁻¹, a weak absorption peak at 2078 cm⁻¹ gradually appeared as the temperature increasing from 30 to 120 °C, which was identified as the active Ir-H species according to the previously reported work ³⁰. Meanwhile, the characteristic peak at 1362 cm⁻¹ attributed to N-C vibration for the targeted product of N-hepthyl-N-methylaniline (see S. Fig. 2 in ESI) was concurrently observed. The accompanying peak at 1871 cm⁻¹ was assigned to Ir-CO species which was the result of the complexation of [Ir(COD)Cl]₂ with CO. Similarly, in CO atmosphere with H_2O as the hydrogen source, the formation of Ir-H species (ν 2078 cm⁻¹) was also observed while the temperature increased up to 140 °C over the L6-based system (Fig. 4). In contrast, over L5-based Ir-catalyst, under CO/H2O condition, the vibration of Ir-H was unobservable at all (see S. Fig. 3 in ESI). The in situ FT-IR analysis indicated that only the presence of the ionic diphosphine of L6 facilitated the formation and stability of Ir-H active species while using H₂O as hydrogen source.



Fig. 3 The *in situ* high-pressure FT-IR spectra recorded from 30 to 120 °C after mixing [Ir(COD)Cl]₂, **L6**, 1-hexene, *N*-methylaniline and NMP in CO/H₂ (2.0 MPa; v_{CO}/v_{H₂} = 3/1)



Fig. 4 The in situ high-pressure FT-IR spectra recorded from 30 to 140 °C after mixing [Ir(COD)Cl]₂, L6, 1-hexene, N-methylaniline, H₂O and NMP in CO (0.5 MPa)

COMMUNICATION

In addition, as an ionic ligand with high polarity, **L6**-based Ircatalyst could be precipitated by *n*-hexane upon completion to fulfil the recovery and recycling uses of transition metal catalysts. As demonstrated(see S. Fig. 4 in ESI), the catalyst could be recycled 7 runs. The ICP-OES analysis indicated that the leaching of Ir and P elements in the combined extract was non-detectable (below the detection limit of 0.1 μ g/g). The decreased activity of the catalyst in the third run and afterwards was mainly due to the physical loss during the transfer of the catalyst. The deactivation of the catalyst was not observed since the reaction solution was always clear and yellow without precipitation of metal blacks.

The scope of hydroaminomethylation catalysed by L6-based Ir-catalyst was explored (see S. Table 2 in ESI). It was found that, as for the linear aliphatic α -olefins, the increased carbon chains led to the decreased reaction rate obviously. For example, 1heptene, 1-octene and 1-dodecene afforded 80~86% yields of the products while 1-hexene corresponded to 93% yield (Entries 2-5 vs 1). The internal aliphatic olefins such as 2-octene and cyclooctene led to very low yields of the amines due to the bulky steric hindrance (Entries 6 and 7). When styrene and its derivatives were applied to repeat the reactions at the prolonged time of 48 h, styrene gave 80% yield of the corresponding amines whereas styrene derivatives with parapositioned substituents afforded the lower yields of the products due to the obvious steric and electronic effects (Entries 8-13). Unfortunately, the uses of the other amines instead of N-methylaniline to perform hydroaminomethylation of 1-hexene universally resulted in the drop of the product yields (Entries 14 and 15).

Conclusions

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L6-based Ir-catalyst was proved highly efficient and recyclable for hydroaminomethylation of different olefins by using H₂O as hydrogen source for the first time. In this protocol, the use of H₂O as the hydrogen source instead of H₂ was advantageous to depress the side-reaction of hydrogenation of olefins. **L6**, as an ionic π -acceptor diphosphine with insensitivity to water and oxygen, rendered the Ir-catalyst high activity towards hydroaminomethylation and good longevity. The *in situ* high pressure FT-IR analysis indicated that over **L6**-based Ir-catalyst, the formation and stability of Ir-H active species (ν 2078 cm⁻¹) was favored, which was responsible for the key step of hydorformylation in the hydroaminomethylation. In addition, the high polarity of **L6** as an ionic compound also facilitated the recyclability of the homogeneous Ir-catalyst.

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Conflicts of interest

There are no conflicts of interest to declare.

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