이학석사 학위논문

Hydrogen-Free Cobalt–Rhodium Heterobimetallic Nanoparticle Catalyzed Reductive Amination of Aldehydes and Ketones with Amines and Nitroarenes in the Presence of Carbon Monoxide and Water

수소 없이 일산화탄소와 물 존재하에 코발트–로듐 불균일 촉매를 이용한 알데하이드/케톤과 아민/나이트로아렌의 환원성 아민화 반응

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Hydrogen-Free Cobalt−Rhodium Heterobimetallic

Nanoparticle Catalyzed Reductive Amination of

Aldehydes and Ketones with Amines and Nitroarenes

in the Presence of Carbon Monoxide and Water

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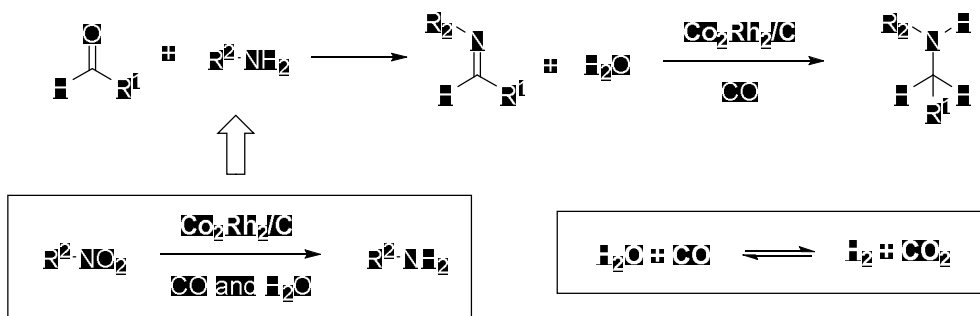A Thesis for M.S. Degree

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Abstract

$$R^2\text{-}NO_2 \xrightarrow[\text{CO and } H_2O]{Co_2Rh_2/C} R^2\text{-}NH_2$$

$$H_2O + CO \rightleftharpoons H_2 + CO_2$$

Cobalt−rhodium heterobimetallic nanoparticle−catalyzed reductive amination of aldehydes and ketones with amines in the presence of 5 atm carbon monoxide without an external hydrogen source has been developed. Water added and generated in situ produces hydrogen via a water−gas−shift reaction. The reaction can be extended to the tandem reduction of aldehydes and ketones with nitroarenes. The catalytic system is stable under the reaction conditions and could be reused eight times without losing any catalytic activity.

Keywords: heterogeneous catalysis, amination, reduction, carbon monoxide, water

Contents

Introduction

Homogeneous transition metal complexes−catalyzed direct reductive amination procedures are well delveloped.[1] Two types of reducing agents are employed for direct reductive amination of aldehyde with amines;[2] based on metal−catalyzed hydrogenation and hydride reducing agents (Scheme 1a).[3] However, the use of hydrogen is not recommendable in an industrial application, considering the risk of explosion. Reducing agents limit many substrates having reducible functionalities and some reducing agents could generate toxic byproducts. Recently, alternatives to the use of hydrogen or hydride have been reported.[4] Chusov and List[5] recently described a Rh−catalyzed reductive amination of aldehydes with aryl amines (Scheme 1b). Their amination utilizes the existing hydrogen atoms of the amine substrates and high pressures of carbon monoxide (20 ~100 bar) as the reductant in THF at $120 \sim 140$ $^{\circ}$C. A method of reduction without an external hydrogen source is a highly desirable process. Inspired by the work, we envisioned in situ generated water as a hydrogen source. If a reductive amination of aldehydes with amines was carried out in the presence of carbon monoxide, the liberated water in the condensation reaction might react with carbon monoxide to give hydrogen and carbon dioxide in the presence of a water−gas−shift reaction catalyst. Then the generated hydrogen molecule can act as a reducing agent, resulting in producing amines. Several decades ago, Iqbal reported the use of

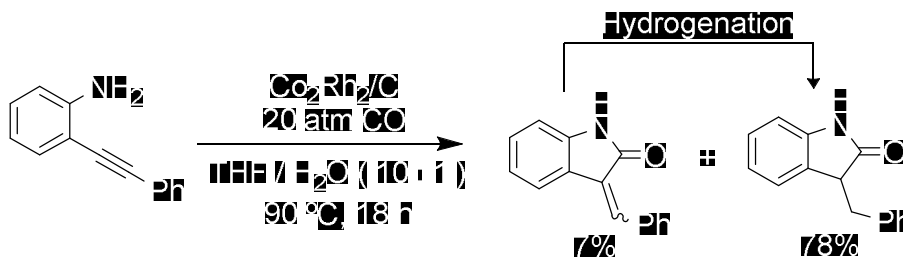carbon monoxide and water in the reduction of a nitro group in nitroarene compounds.[6]
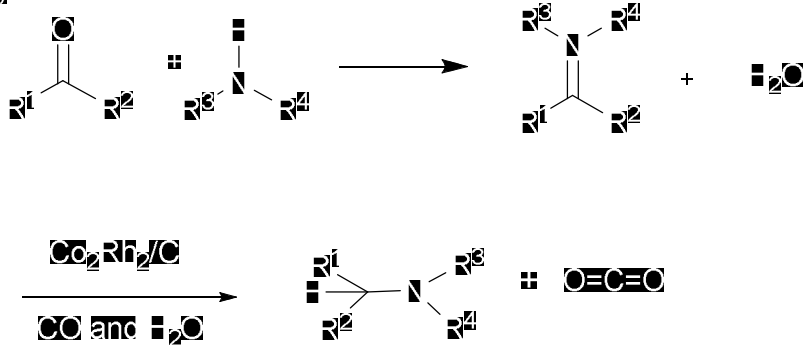
a) Previous work

b) Chusov and List's work

70-98 % (without H$_2$O)
6-16 % (solvent/H$_2$O = 3:1)
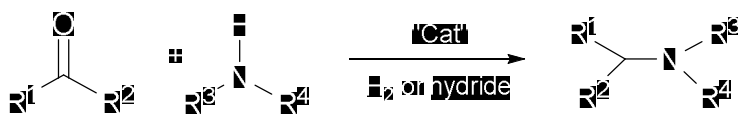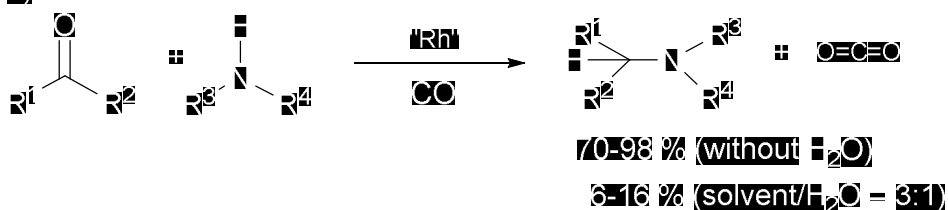
c) Our previous work


d) This work

Scheme 1. Reductive Amination Reactions[3,5] / Hydrogenation[10]

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The emergence of transition metal nanoparticles has led to an explosive growth in catalysis.[7] Transition metal nanoparticles are potentially attractive catalysts due to their high catalytic activities and synergistic effects. Recently, the use of heterobimetallic nanoparticles as catalysts has attracted much attention because their catalytic performance is generally superior to that of a single nanoparticle by itself and there is potential to create new types of catalysts for reactions which may not be achieved by monometallic catalyst.[8] We reported that cobalt/rhodium heterobimetallic nanoparticles (Co_2Rh_2, derived from $Co_2Rh_2(CO)_{12}$) immobilized on charcoal (Co_2Rh_2/C) were quite useful catalysts in carbonylation[9] and/or hydrogenation reactions (Scheme 1c).[10] In the hope of finding new catalytic amination system, we decided to use Co_2Rh_2/C as catalyst in the reductive amination between aldehydes (or ketones) and amines in the presence of carbon monoxide without any external hydrogen source. We found that the catalytic system was quite effective in the reductive amination of aldehydes or ketones with amines in the presence of 5 atm CO in wet THF at 100 °C for 12 h (Scheme 1d). We herein report our results. Recently, Franke and Beller reported[11] Ru-catalyzed hydroaminomethylation of olefins with an amine using a water-gas shift reaction (40 bar CO used). The Co_2Rh_2/C-catalyzed reductive amination could be conducted at substantially lesser pressure than the one previously employed under rhodium and ruthenium catalysis.[5,12]

Results and Discussion

Initially, the reaction of benzaldehyde (**1a**) with 4-methoxyaniline (**2a**) to afford the amination product, N-benzyl-4-methoxyaniline (**3aa**), was chosen as the model reaction in the presence of Co_2Rh_2/C (5 mol%) in THF at 100 °C (Scheme 2). After workup, **3aa** was isolated in 65% yield with a concomitant formation of an imine, N-(4-methoxyphenyl)-1-phenylmethanimine, **4aa**, in 20% yield.
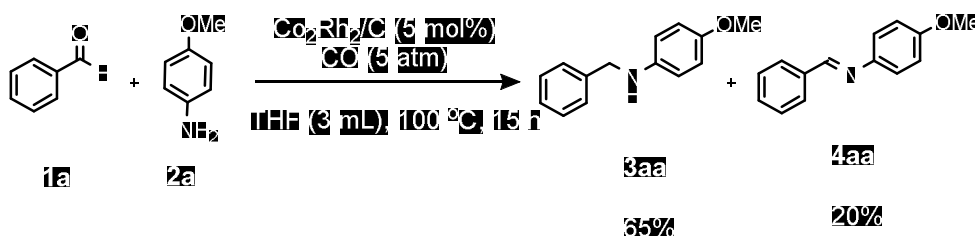

Scheme 2. Initial observation

Encouraged by the above observation, we decided to optimize the reaction conditions for the amination of **1a** with **2a** under 5 atm CO (Table 1). Decreasing the reaction time from 12 h to 6 h led to formation of a mixture of **3aa** and **4aa** in 52% and 20%, respectively (entry 2). In the presence of molecular sieves (3Å), no amine product was isolated. Instead, **4aa** was isolated in 98% yield (entry 3). This observation suggested that water was needed for hydrogenation of **4aa**. Water generated in the formation of **4aa** would react with carbon monoxide by means of the water–gas shift reaction to produce molecular hydrogen and carbon dioxide. Thus, we varied the amount of water in the reaction mixture (water/THF, from 0.3

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mL/3.0 mL to 0.03 mL/3.0 mL) to know how the water concentration influences the hydrogenation of **4aa** (entry 4 vs 7).The reaction was highly sensitive to the reaction temperatureand the amount of catalyst used (entry 4 vs 5). Lowering the reaction temperature from 100 ^{o}C to 85 ^{o}C completely blocked the formation of an amine. Moreover, the reaction was highly sensitive to the amount of Co_2Rh_2/C used (entry 4 vs 6). Decreasing the amount of catalyst from 5 mol% to 3 mol% led to the formation of a mixture of **3aa** and **4aa** in 54 % and 44% yield, respectively. The best yield (97%) of **3** was observed when the reaction carried out in the presence of 5 mol% of Co_2Rh_2/C in a mixturesolvent of water and THF (0.03 mL/3.0 mL) at 100°C for 6 h. When the reaction was carried out at 120°C (entry 8), the reaction time could be shortened with a high yield (95%). The reaction was highly sensitive to the CO pressure and reaction time. Under 3 atm of CO, a mixture of **3aa** and **4aa** was formed in 17% and 80% yields, respectively (entry 9). For 3 h of reaction time, a mixture of **3aa** and **4aa** was obtained in 23% and 75% yields, respectively (entry 10). When the same reaction was carried out in toluene, **4aa** was obtained as the sole product (entry 11). Therefore, the optimum reaction conditions were as follows: 5 mol% Co_2Rh_2/C in 0.03 mL H_2O and 3.0 mL THF at 100°C for 6 h of reaction time. In general, strict anhydrous conditions are favorable in the transition metal−catalyzed reductive amination and it is operationally troublesome to keep anhydrous conditions during a reaction. However, the present operationally simple catalytic system was quite effective for the amination in the presence of water, using

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the solvent (THF) without purification.
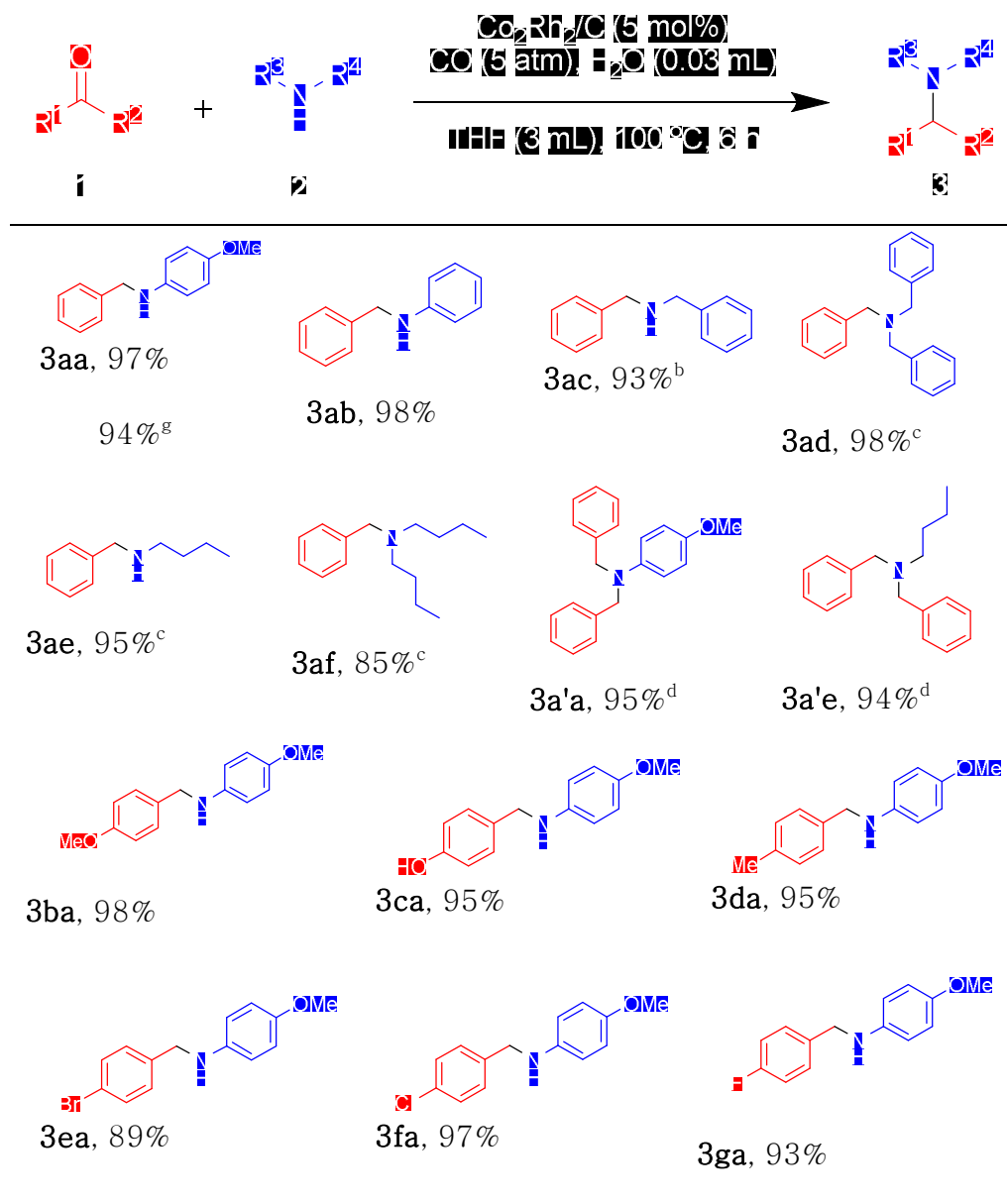
Table 1. Optimization of the Reaction Conditions
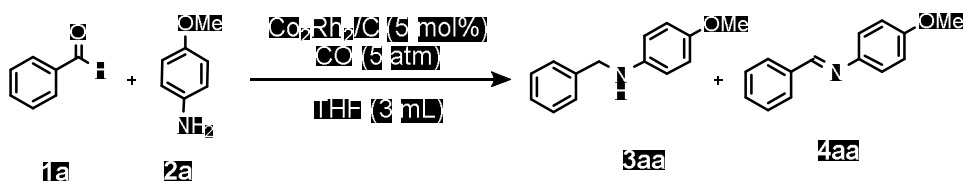
Entry	H$_2$O (mL)	Temp (°C)	Time (h)	Yield (%)[a]	
				3aa	4aa
1	0	100	15	65	20
2	0	100	6	52	20
3[b]	0	100	6	0	98
4	0.3	100	6	94	0
5	0.3	85	6	0	98
6[c]	0.3	100	6	54	44
7	0.03	100	6	97	0
8	0.03	120	3	95	0
9[d]	0.03	100	6	17	80
10	0.03	100	3	23	75
11[e]	0.03	100	6	0	97

[a] Isolated yield. [b] In the presence of molecular sieves (3Å). [c] 3 mol% Co$_2$Rh$_2$/C used. [d] Under 3 atm CO. [e] In toluene.

With the optimized reaction conditions in hands, the substrate scope of the reaction was examined (Table 2). The amination reaction found to be effective for all relevant substrates, including aromatic and aliphatic primary and secondary amines as well as aliphatic and aromatic aldehydes and ketones. Both electron−donating (OMe, OH, and Me) and −withdrawing (F, Cl, Br, CF$_3$) groups on the aromatic substituents of the aldehydes and amines are tolerated. Functional groups such as hydroxyl and halo groups are tolerant in the reaction. However, a vinyl group is completely hydrogenated (**3ag**). The reductive amination reaction shows excellent generality for a variety of aldehydes and primary and secondary amines with very good to excellent yields. The lowest yield (**3ak**, 82%) was observed with 4−fluoroaniline. Generally, the use of an aryl aldehyde or aryl amine gave a relatively higher yield than that of an aliphatic aldehyde (**3ma**, 84%), ketone (**3la**, 86%), or amine (**3af**, 85%) used. When 2 equiv of an aldehyde was used, a tertiary−amine with two substituents from the aldehyde was isolated in excellent yields (**3a'a**; 95%: **3a'e**; 94%). When a secondary amine with two different substituents was reacted with another aldehyde, an unsymmetrical tertiary amine having three different substituents was isolated in high yields. Reaction of *N*−benzyl−4−methoxyaniline (**3aa**) with 4−methoxybenzaldehyde (**1b**) afforded *N*−benzyl−4−methoxy−*N*−phenylaniline (**3bl**) in 88% yield. Thus, the catalytic reaction process developed in this study provided an easy way to make secondary and tertiary amines from various aldehydes and amines. In addition, the reaction can be conducted on a gram−scale (2.0 g of

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3aa, 94% yield). However, when acetophenone was used as a carbonyl compound, no amination was observed.

Table 2. Amination of Aldehydes and Ketones with Amines[a]

3aa, 97%
94%[g]

3ab, 98%

3ac, 93%[b]

3ad, 98%[c]

3ae, 95%[c]

3af, 85%[c]

3a'a, 95%[d]

3a'e, 94%[d]

3ba, 98%

3ca, 95%

3da, 95%

3ea, 89%

3fa, 97%

3ga, 93%

3ha, 90%

3ag, 87%[e]

3ah, 95%

3ai, 98%

3aj, 91%

3ak, 82%

3bl, 88%[f]

3ia, 96%

3ja, 96%[c]

3ka, 96%

3la, 86%[c]

3ma, 84%[c]
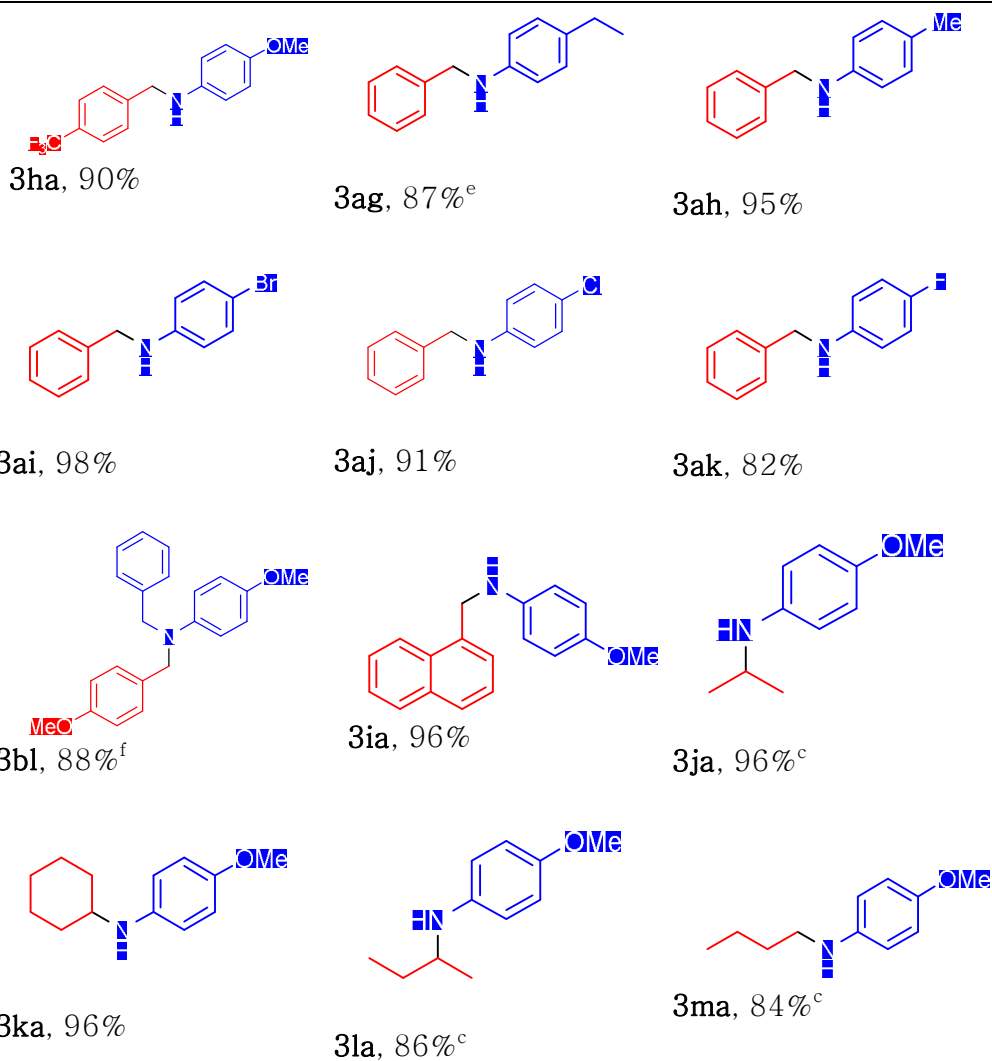
[a] Reaction conditions: aldehyde (1.0 mmol), amine (1.0 mmol), H_2O (0.03 mL), CO (5 atm), and Co_2Rh_2 catalyst (5 mol%, 90 mg) in 3 mL THF at 100 °C for 6 h, Isolated yield. [b] 6 h and 130 °C. [c] 12 h and 130 °C. [d] aldehyde (2.0 mmol) used, 14 h, 130 °C. [e] 4−vinylaniline used. [f] 14 h and 100 °C. [g] gram scale (2.0 g of **3aa**)
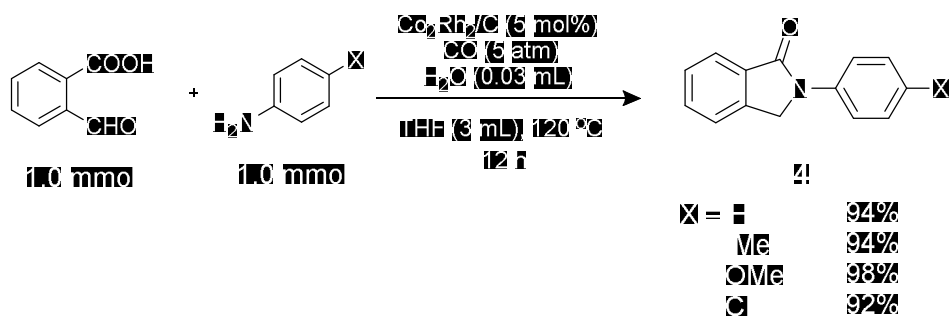
Scheme 3. Synthesis of Isoindolin-1-ones

The amination of aldehydes can be extended to the reactions of 2-formylbenzoic acid. Reaction of 2-formylbenzoic acid with anilines afforded excellent yields of isoindolin-1-ones (**4**) (Scheme 3). The highest yield (98%) was observed with 4-methoxyaniline.
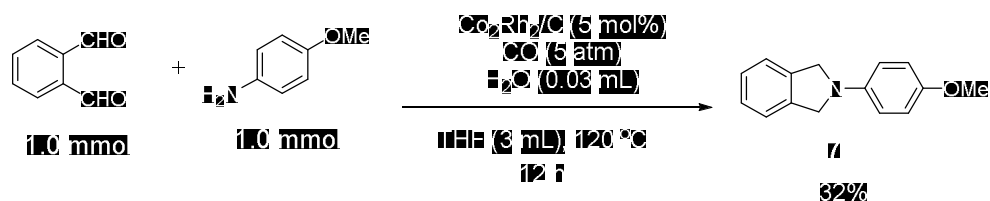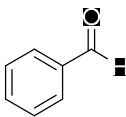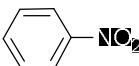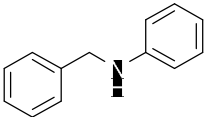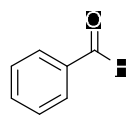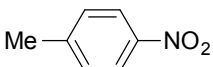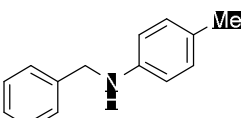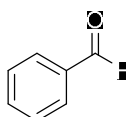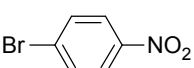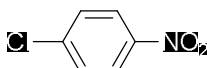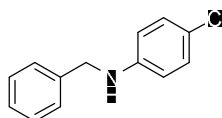

Scheme 4. Synthesis of isoindoline
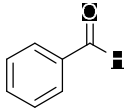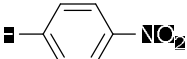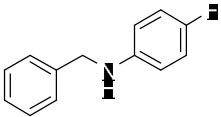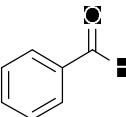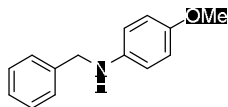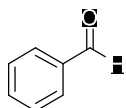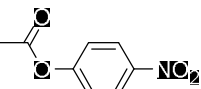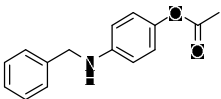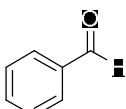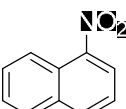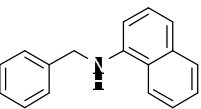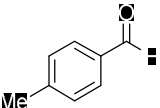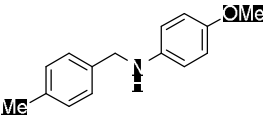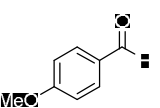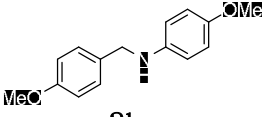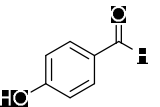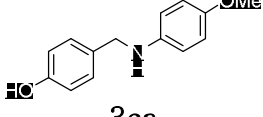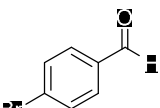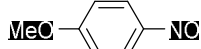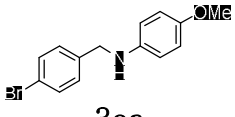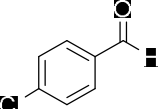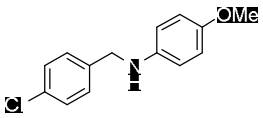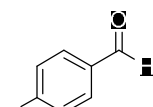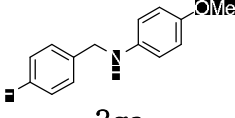
However, the reaction of phthaldehyde with an amine afforded an isoindoline (**7**) in a low yield (32%) (Scheme 4).
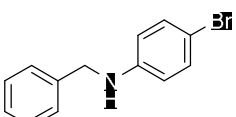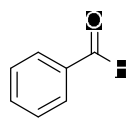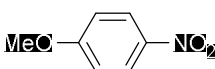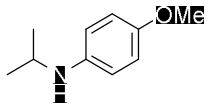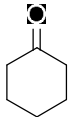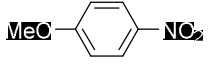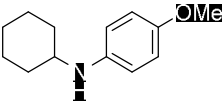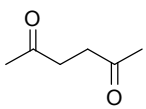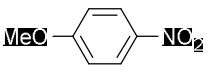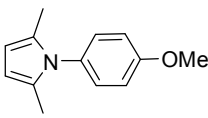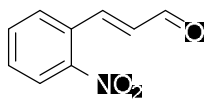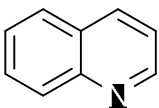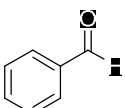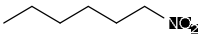
Generally, aromatic amines are produced by a catalytic reduction of nitroarenes.[13] Therefore, the use of nitroarenes instead of aromatic amines in the reductive amination of aldehydes is highly desirable because it does not need prior reduction of the respective nitroarenes. Hydrogenation of nitroarenes over catalyst in the

presence of CO and water has long history.[14] However, the tandem reductive amination is relatively rare.[15] It is still highly desirable to develop an effective catalyst for this transformation. Thus, we decided to study the use of nitroarenes as an amine source in the amination of aldehydes and ketones. The optimum reaction conditions were as follows: 5 mol% Co_2Rh_2/C in 0.15 mL H_2O and 3.0 mL THF at 120 ^oC for 24 h (for screening the reaction conditions, see SI). The results were summarized in Table 3.

Table 3. Amination of Aldehydes and Ketones with Nitroarenes.[a]

Entry	Aldehyde or Ketone	Nitroarene	Product	Yield (%)[b]
1			3ab	92
2		Me—⟨ ⟩—NO_2	3ah	90
3		Br—⟨ ⟩—NO_2	3ai	90
4			3aj	76

#				Yield
5	(benzaldehyde/acetophenone)	O₂N–C₆H₄–	3ak	75
6		MeO–C₆H₄–NO₂	3aa	93
7		AcO–C₆H₄–NO₂	3al	91
8		1-nitronaphthalene	3am	90
9	Me–C₆H₄–	MeO–C₆H₄–NO₂	3da	89
10	MeO–C₆H₄–	MeO–C₆H₄–NO₂	3ba	90
11	HO–C₆H₄–	MeO–C₆H₄–NO₂	3ca	92
12	Br–C₆H₄–	MeO–C₆H₄–NO₂	3ea	87
13	Cl–C₆H₄–	MeO–C₆H₄–NO₂	3fa	80
14	I–C₆H₄–	MeO–C₆H₄–NO₂	3ga	84

15	(acetone)	MeO—C6H4—NO2	isopropyl-N-(4-methoxyphenyl)amine 3ja	74
16	(cyclohexanone)	MeO—C6H4—NO2	cyclohexyl-N-(4-methoxyphenyl)amine 3ka	88
17	(hexane-2,5-dione)	MeO—C6H4—NO2	2,5-dimethyl-1-(4-methoxyphenyl)pyrrole 5	93
18	(2-nitrocinnamaldehyde)		quinoline 6	90
19	(acetophenone)	hexyl—NO2	N.R.	

[a] Reaction conditions: aldehyde (0.5 mmol), nitroarene (0.5 mmol), H_2O (0.15 mL), CO (5 atm) and Co_2Rh_2 catalyst (5 mol%, 45 mg) in 3 mL THF at 120 °C for 24 h. [b] Isolated yield.

All the yields observed with nitroarenes (entries 1 ~ 16) were slightly lower than those observed with amines. However, as shown in the Table 2, the reactions of benzaldehyde with various nitroarenes except with 4-fluoro- and 4-chloroaniline still afforded N-benzyl-anilines in excellent yields. With 4-fluoro and 4-chloroanilines (entries 4 and 5), the corresponding secondary amines were isolated in 75% and 76% yield, respectively. Interestingly, the reaction was tolerant of an ester group (entry 7). 1-Nitronaphthalene also afforded an excellent yield (90%) of the corresponding amine (entry 8). Benzaldehydes having an electron-

withdrawing group afforded slightly lower yields than those with an electron−donating group (entries 9 − 11 *vs* 12 − 14). Aliphatic ketones such as acetone and cyclohexanone also afforded the corresponding amines in high yields (entries 15 and 16).However, acetone (74%) was not a good substrate as cyclohexanone (88%). Reaction of 1−methyoxy−4−nitrobenzene with 2,5−hexandione afforded 1−(4−methoxyphenyl)−2,5−dimethyl−1*H*−pyrrole (**5**), in 94% yield (entry 17). An intramolecular reaction of 3−(2−nitrophenyl)acrylaldehyde afforded quinolone (**6**) in 92% yield (entry 18). For entries 17 and 18, the reduction of nitro group was observed, but the reductive amination product was not formed. The amination of aldehydes and ketones with nitroarenes were quite effective under our reaction conditions. However, when 1−nitrohexane was used as a nitrogen source, no amination was observed.

 When a reaction of benzaldehyde with 1−methoxy−4−nitromethoxybenzene was conducted in the presence of D_2O, deuterated amine was observed (Scheme 5). Thus, sequential reactions of hydrogenation and amination occurred under our reaction conditions.
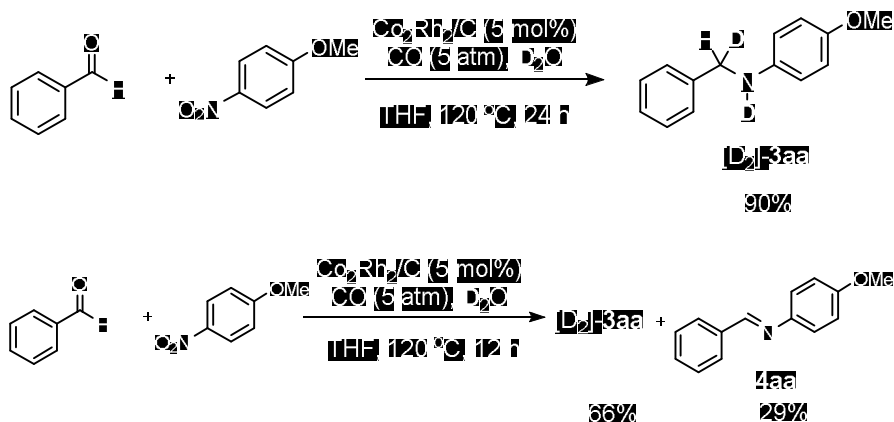
Scheme 5. Deuterium Labelling Experiment

When we used hydrogen itself instead of carbon monoxide under identical conditions, the expecting product was obtained with a comparable yield (Scheme 6).
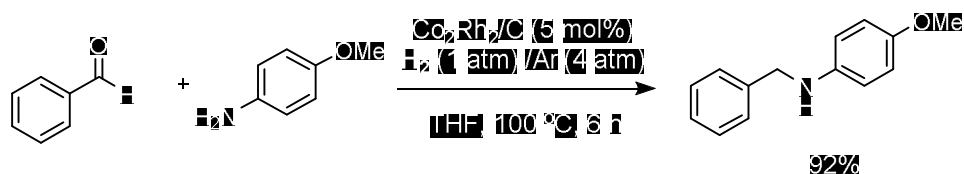
Scheme 6. Reductive Amination with Hydrogen Gas

The reusability of Co_2Rh_2/C was also examined for the amination of **1a** with **2a** (Table 4). After reaction, the catalyst was filtered from the reaction mixture, dried in vacuum, and reused for the further catalytic reaction. The catalytic system is stable under the reaction conditions. The catalyst maintained its high level of activity even after being reused eight times (97%, 95%, 94%, 92%, 92%, 93%, 90%, and 92%, respectively); the maximum reusability has not been tested.

Table 4. Reuse of Co_2Rh_2/C Catalyst for Reductive Amination of 1a with 2a [a]
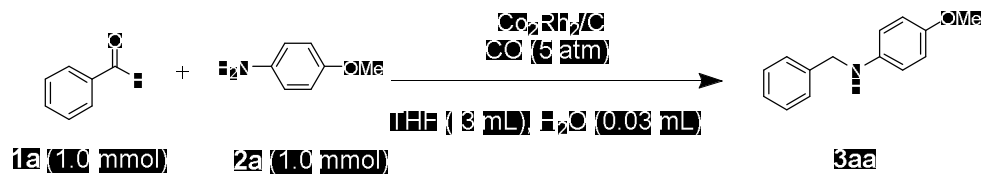
Entry	Catalyst	Yield (%)[b]
1	Co_2Rh_2 5 mol%	97
2	Recovered from #1	95
3	Recovered from #2	94
4	Recovered from #3	92
5	Recovered from #4	92
6	Recovered from #5	93
7	Recovered from #6	90
8	Recovered from #7	92

[a]1a (1.0 mmol), 2a (1.0 mmol), H_2O (0.03 mL), CO (5 atm), and Co_2Rh_2 catalyst (5 mol%, 90 mg) in 3 mL THF at 100 ^{o}C for 6 h. [b]Isolated yield.

Conclusion

We have developed the first Co_2Rh_2 nanoparticles/charcoal−catalyzed reductive amination of aldehydes and ketones with amines using a water−gas−shift reaction instead of hydrogen. Advantageously, no complicated ligands or additional acid or base is needed. The reaction can be extended to the tandem reduction of aldehydes and ketones with nitroarenes. The experimental simplicity and the reusability are especially attractive and should encourage the use of this catalytic system among synthetic chemists and in industrial application. Further investigations of the present catalytic system to other reactions are ongoing in our laboratory.

Experimental Section

1. General Remarks

Workup procedures were done in air. THF, hexane, and ethyl acetate were used without further purification. Unless otherwise noted, all commercial materials were used without purification. High purity CO (99.95%) was used. TLC analysis of reaction mixtures was performed on Merck silica gel 60 F254 TLC plates. TLC plates were visualized by ultraviolet light and treated with acidic $p-$ anisaldehyde stain followed by gentle heating. Flash column chromatography was carried out on Merck 60 silica gel (230 – 400 mesh). ^{1}H and ^{13}C NMR spectra were recorded with Agilent 400– MR DD2 (400 MHz and 100 MHz, respectively) spectrometer. ^{1}H NMR spectra were taken in CDCl$_3$ and were referenced to residual TMS (0 ppm) and reported as follows: chemical shift (δ ppm), multiplicity (s = singlet, d= doublet, t = triplet, q = quartet, m = multiplet), coupling constant (Hz), and integration. Chemical shifts of the ^{13}C NMR spectra were measured relative to CDCl$_3$ (77.16 ppm) or acetone−d$_6$ (29.84 ppm). High−Resolution Mass Spectra were obtained at the Korea Basic Science Institute (Daegu, South Korea) on a Jeol JMS 700 high resolution mass spectrometer. Compounds 3aa,[1] 3ab,[1] 3ac,[1] 3ad,[2] 3ae,[3] 3af,[4] 3ag,[5] 3ah,[1] 3ai,[1] 3aj,[1] 3ak,[1] 3am,[4] 3ba,[1] 3ca,[6] 3da,[1] 3ea,[1] 3fa,[1] 3ga,[1] 3ha,[1] 3ia,[7] 3ja,[1] 3ka,[1] 3la,[8] 3ma,[9] 3a' a,[10] 3a' e,[11] 4aa[12], 4a,[13] 4b,[13] 4c,[13] 4d,[13] 5, [14] and 6 [15] were known compounds.

2. Immobilization of Co/Rh Nanoparticles on Charcoal[16]

To a two-neck flask were added *o*-dichlorobenzene (10 mL), oleic acid (0.2 mL), and trioctylphosphine oxide (0.4 g). While the solution was heated at 180℃, a solution of metal carbonyl $Co_2Rh_2(CO)_{12}$ (0.8 g) in 25 ml *o*-dichlorobenzene was injected into the flask. The resulting solution was heated to 180 ℃ for 2 h and then concentrated to a volume of 5 mL. The concentrated solution was cooled to room temperature. To the cooled solution were added 30 mL of THF. After the solution was well stirred for 10 min, flame-dried charcoal (1.6 g) was added to the solution. After the resulting solution had been refluxed for 12 h, the precipitates were filtered and washed with diethyl ether (20 mL), dichloromethane (20 mL), acetone (20 mL), and methanol (20 mL). Vacuum drying gave a black solid.

3. General Procedure

A. General procedure for Co_2Rh_2-catalyzed reductive amination of aldehydes/ketones with amines
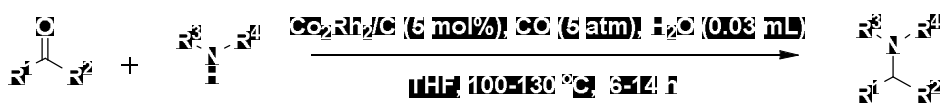
Reactions were performed in a 30 mL stainless steel autoclave equipped with a stirring bar and the followings were placed in the autoclave in the order: amine (1.0 mmol), aldehyde/ketone (1.0 mmol), THF (3 mL), H_2O (0.03 ml), and 5 mol % Co_2Rh_2 (90 mg of

the immobilized Co_2Rh_2/C). The reactor was purged with CO gas, and charged with 5 atm of CO and heated at 100 ~ 140 ℃ for 6 ~ 14 h. After the reactor was cooled to room temperature, the solution was filtered and concentrated, and the product was isolated by chromatography on a silica gel column eluting with hexane and ethyl acetate.

B. Gram-scale experiment

C. General proxcedure for Co_2Rh_2-catalyzed reductive amination of aldehydes/ketones with nitro compounds
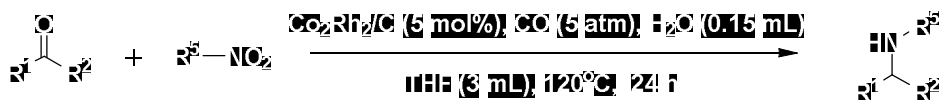
Reactions were performed in a 30 mL stainless steel autoclave equipped with a stirring bar and the followings were placed in the autoclave in the order: nitro compound (0.5 mmol), aldehyde/ketone (0.5 mmol), THF (3 mL), H_2O (0.15 mL), and 5mol % Co_2Rh_2 (45 mg of the immobilized Co_2Rh_2/C). The reactor was purged with CO gas, and charged with 5 atm of CO and heated at 120 ℃ for 24 h. After the reactor was cooled to room temperature, the solution was filtered and concentrated, and the product was isolated by

chromatography on a silica gel column eluting with hexane and ethyl acetate.

Table S1. Optimization of the reaction conditions for the reductive amination of benzaldehyde with 4-nitroanisole
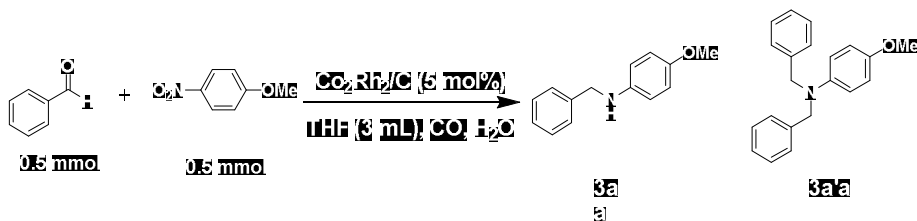
Entry	CO (atm)	H$_2$O (mL)	Temp (°C)	Time (h)	Yield (%)[a]	
					3aa	3a' a
1	5	0.03	100	6	5	0
2	5	0.15	100	6	14	0
3	5	0.15	100	12	54	0
4	5	0.15	100	24	90	0
5	5	0.15	120	24	93	0
6	5	0.15	120	12	71	0
7	8	0.15	120	12	85	5
8	10	0.15	120	12	79	9
9	10	0	120	12	0	0

[a] Isolated yield.

4. Procedure for reductive amination with 5 atm of H_2 and Ar (1 : 4)
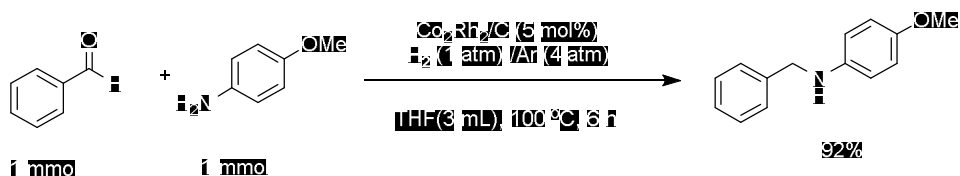
Reactions were performed in a 30 mL stainless steel autoclave equipped with a stirring bar and the followings were placed in the autoclave in the order: p-anisidine (1.0 mmol), benzaldehyde (1.0 mmol), THF (3 mL) and 5 mol % Co_2Rh_2 (90 mg of the immobilized Co_2Rh_2/C). The reactor was purged with Ar gas, and charged with 5 atm of Ar and H_2 (4 : 1) and heated at 100 ℃ for 6 h. After the reactor was cooled to room temperature, the solution was filtered and concentrated, and the product was isolated by chromatography on a silica gel column eluting with hexane and ethyl acetate.

5. Deuterium labeling experiments
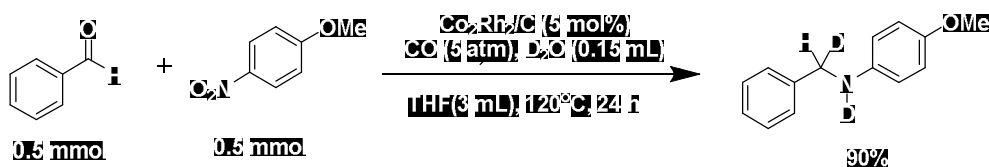
Reactions were performed in a 30 mL stainless steel autoclave equipped with a stirring bar and the followings were placed in the autoclave in the order: 4-nitroanisole (0.5 mmol), benzaldehyde (0.5 mmol), THF (3 mL), D_2O (0.15 mL), and 5mol % Co_2Rh_2 (45 mg of the immobilized Co_2Rh_2/C). The reactor was purged with CO gas, and charged with 5 atm of CO and heated at 120 ℃ for 24 h. After the reactor was cooled to room temperature, the solution was

filtered and concentrated, and the product was isolated by chromatography on a silica gel column eluting with hexane and ethyl acetate.

8. Characterization Data for Isolated Products

N-Benzyl-4-methoxyaniline (3aa)

Yellow solid; m.p. = 50℃; ^{1}H NMR (400 MHz, CDCl$_3$) δ (ppm): 7.35 (m, 4 H), 7.27 (d, *J* = 6.9 Hz, 1 H), 6.77 (d, *J* = 8.8 Hz, 2 H), 6.60 (d, *J* = 8.8 Hz, 2 H), 4.28 (s, 2 H), 3.77 (s, 1 H), 3.74 (s, 3 H); ^{13}C NMR (101 MHz, CDCl$_3$) δ (ppm): 152.30, 142.58, 139.81, 128.73, 127.68, 127.30, 115.03, 114.22, 55.94, 49.38; HRMS (EI[+]): m/z calcd for [C$_{14}$H$_{15}$NO][+] : 213.1154, found 213.1152.

4-Methoxy-*N*-(4-methoxybenzyl)aniline (3ba)

White solid; m.p. = 97 ℃; ^{1}H NMR (400 MHz, CDCl$_3$) δ (ppm): 7.28 (d, *J* = 8.4 Hz, 2 H), 6.87 (d, *J* = 8.5 Hz, 2 H), 6.77 (d, *J* = 8.8 Hz, 2 H), 6.59 (d, *J* = 8.8 Hz, 2 H), 4.19 (s, 2 H), 3.79 (s, 3 H), 3.73 (s, 3 H); ^{13}C NMR (101 MHz, CDCl$_3$) δ (ppm): 158.78, 152.12, 142.52, 131.66, 128.81, 114.87, 114.09, 113.96, 55.79, 55.28, 48.70; HRMS (EI[+]): m/z calcd for [C$_{15}$H$_{17}$NO$_2$][+] : 243.1259, found 243.1261.

4-Methoxy-*N*-(4-methylbenzyl)aniline (3da)

White solid; m.p. = 107 ℃; ^{1}H NMR (400 MHz, CDCl$_3$) δ (ppm): 7.26 (d, *J* = 7.8 Hz, 2 H), 7.15 (d, *J* = 7.8 Hz, 2 H), 6.77 (d, *J* = 8.8

Hz, 2 H), 6.60 (d, J = 8.8 Hz, 2 H), 4.23 (s, 2 H), 3.74 (s, 4 H), 2.34 (s, 3 H); ^{13}C NMR (101 MHz, CDCl$_3$) δ (ppm): 152.24, 142.65, 136.91, 136.72, 129.38, 127.66, 115.01, 114.19, 55.93, 49.11, 21.23; HRMS (EI$^+$): m/z calcd for [C$_{15}$H$_{17}$NO]$^+$: 227.1310, found 227.1309.

4-(((4-Methoxyphenyl)amino)methyl)phenol (3ca)

White solid; m.p. = 109 ℃; ^{1}H NMR (400 MHz, Acetone-d$_6$) δ (ppm): 8.18 (s, 1 H), 7.21 (d, J = 8.3 Hz, 2 H), 6.78 (d, J = 8.4 Hz, 2 H), 6.71 (d, J = 8.9 Hz, 2 H), 6.61 (d, J = 8.9 Hz, 2 H), 4.85 (s, 1 H), 4.16 (s, 2 H), 3.66 (s, 3 H); ^{13}C NMR (101 MHz, Acetone-d$_6$) δ (ppm): 157.21, 152.68, 144.20, 132.08, 129.56, 116.00, 115.44, 114.62, 55.84, 48.74; HRMS (EI$^+$): m/z calcd for [C$_{14}$H$_{15}$NO$_2$]$^+$: 229.1103, found 229.1105.

N-(4-Bromobenzyl)-4-methoxyaniline (3ea)

Yellow oil; ^{1}H NMR (400 MHz, CDCl$_3$) δ (ppm): 7.44 (d, J = 7.0 Hz, 2 H), 7.23 (d, J = 8.0 Hz, 2 H), 6.74 (d, J = 1.4 Hz, 2 H), 6.55 (d, J = 7.6 Hz, 2 H), 4.23 (s, 2 H), 3.79 (s, 1 H), 3.72 (s, 3 H); ^{13}C NMR (101 MHz, CDCl$_3$) δ (ppm): 152.62, 142.33, 139.10, 131.96, 129.40, 121.15, 115.21, 114.45, 56.09, 48.86; HRMS (EI$^+$): m/z calcd for [C$_{14}$H$_{14}$BrNO]$^+$: 291.0259, found 291.0256.

N-(4-Chlorobenzyl)-4-methoxyaniline (3fa)

White solid; m.p. = 73 ℃; ^{1}H NMR (400 MHz, CDCl$_3$) δ (ppm): 7.28 – 7.17 (m, 4 H), 6.73 (d, J = 8.8 Hz, 2 H), 6.51 (d, J = 8.8 Hz,

2 H), 4.18 (s, 2 H), 3.77 (s, 1 H), 3.68 (s, 3 H); ^{13}C NMR (101 MHz, CDCl$_3$) δ (ppm): 152.18, 142.03, 138.27, 132.63, 128.68, 128.60, 114.83, 114.06, 55.65, 48.34; HRMS (EI$^+$): m/z calcd for [C$_{14}$H$_{14}$ClNO]$^+$: 247.0764, found 247.0767.

N-(4-Fluorobenzyl)-4-methoxyaniline (3ga)

Yellow oil; ^{1}H NMR (400 MHz, CDCl$_3$) δ 7.33 (m, 2H), 7.02 (t, J = 8.6 Hz, 2H), 6.77 (d, J = 8.8 Hz, 2H), 6.59 (d, J = 8.8 Hz, 2H), 4.25 (s, 2H), 3.75 (s, 1H), 3.74 (s, 3H); ^{13}C NMR (101 MHz, CDCl$_3$) δ (ppm): 162.09 (d, J = 245.0 Hz), 152.36, 142.31, 135.49, 129.12 (d, J = 8.0 Hz), 115.47 (d, J = 21.3 Hz), 114.99, 114.23, 55.86, 48.59; HRMS (EI$^+$): m/z calcd for [C$_{14}$H$_{14}$FNO]$^+$: 231.1059, found 231.1060.

4-Methoxy-*N*-(4-(trifluoromethyl)benzyl)aniline (3ha)

Yellow oil; ^{1}H NMR (400 MHz, CDCl$_3$) δ (ppm) : 7.56 (d, J = 8.1 Hz, 2 H), 7.45 (d, J = 8.0 Hz, 2 H), 6.76 (d, J = 8.9 Hz, 2 H), 6.55 (d, J = 8.9 Hz, 2 H), 4.33 (s, 2 H), 3.88 (s, 1 H), 3.71 (s, 3 H); ^{13}C NMR (101 MHz, CDCl$_3$) δ (ppm): 152.49, 144.17, 142.00, 129.44 (q, J = 32.4 Hz), 127.59, 125.60 (q, J = 3.8 Hz), 122.99, 115.04, 114.24, 55.83, 48.73; HRMS (EI$^+$): m/z calcd for [C$_{15}$H$_{14}$F$_3$NO]$^+$: 281.1027, found 281.1028.

N-Benzylaniline (3ab)

White solid; m.p. = 39 ℃; ^{1}H NMR (400 MHz, CDCl$_3$) δ (ppm) : 7.39 – 7.21 (m, 5 H), 7.15 (t, J = 7.8 Hz, 2 H), 6.70 (t, J = 7.3 Hz,

1 H), 6.61 (d, J = 7.8 Hz, 2 H), 4.29 (s, 2 H), 3.97 (s, 1 H); ^{13}C NMR (101 MHz, CDCl$_3$) δ (ppm): δ 148.24, 139.54, 129.36, 128.72, 127.59, 127.31, 117.64, 112.93, 48.39; HRMS (EI$^+$): m/z calcd for [C$_{13}$H$_{13}$N]$^+$: 183.1048, found 183.1050.

N-Benzyl-4-methylaniline (3ah)

Yellow oil; ^{1}H NMR (400 MHz, CDCl$_3$) δ (ppm) : 7.37 – 7.28 (m, 4 H), 7.24 (d, J = 8.1 Hz, 1 H), 6.97 (d, J = 8.4 Hz, 2 H), 6.54 (d, J = 8.3 Hz, 2 H), 4.27 (s, 2 H), 3.86 (s, 1 H), 2.22 (s, 3 H); ^{13}C NMR (101 MHz, CDCl$_3$) δ (ppm): 146.02, 139.77, 129.84, 128.69, 127.58, 127.23, 126.80, 113.08, 48.71, 20.51; HRMS (EI$^+$): m/z calcd for [C$_{14}$H$_{15}$N]$^+$: 197.1204, found 197.1205.

N-Benzyl-4-ethylaniline (3ag)

Yellow oil; ^{1}H NMR (400 MHz, CDCl$_3$) δ (ppm) : 7.40 – 7.24 (m, 5 H), 7.01 (d, J = 8.2 Hz, 2 H), 6.59 (d, J = 8.4 Hz, 2 H), 4.30 (s, 2 H), 3.90 (s, 1 H), 2.54 (q, J = 7.6 Hz, 2 H), 1.19 (t, J = 7.6, 3 H); ^{13}C NMR (101 MHz, CDCl$_3$) δ (ppm): 146.45, 139.98, 133.72, 128.90, 128.88, 127.83, 127.46, 113.26, 48.96, 28.25, 16.29; HRMS (EI$^+$): m/z calcd for [C$_{15}$H$_{17}$N]$^+$: 211.1361, found 211.1359.

N-Benzyl-4-bromoaniline (3ai)

Yellow solid; m.p. = 51 ℃; ^{1}H NMR (400 MHz, CDCl$_3$) δ (ppm) : 7.37 – 7.25 (m, 5 H), 7.23 (d, J = 8.0 Hz, 2 H), 6.49 (d, J = 8.0 Hz, 2 H), 4.28 (s, 2 H), 4.06 (s, 1 H); ^{13}C NMR (101 MHz, CDCl$_3$) δ (ppm): 147.17, 138.98, 132.05, 128.83, 127.51, 114.53, 109.23, 48.35; HRMS (EI$^+$): m/z calcd for [C$_{13}$H$_{12}$BrN]$^+$: 261.0153, found

261.0153.

N-Benzyl-4-chloroaniline (3aj)

Yellow solid; m.p. = 45 ℃; ^{1}H NMR (400 MHz, CDCl$_3$) δ (ppm): 7.33 (d, J = 4.4 Hz, 4 H), 7.30 – 7.24 (m, 1 H), 7.09 (d, J = 8.8 Hz, 2 H), 6.53 (d, J = 8.8 Hz, 2 H), 4.27 (s, 2 H), 4.04 (s, 1 H); ^{13}C NMR (101 MHz, CDCl$_3$) δ (ppm): 146.75, 139.04, 129.18, 128.82, 127.53, 127.49, 122.19, 114.02, 48.45; HRMS (EI^{+}): m/z calcd for [C$_{13}$H$_{12}$ClN]$^{+}$: 217.0658, found 217.0661.

N-Benzyl-4-fluoroaniline (3ak)

Yellow oil; ^{1}H NMR (400 MHz, CDCl$_3$) δ (ppm) : 7.43 – 7.28 (m, 5H), 6.92 (m, 2H), 6.58 (m, 2H), 4.31 (s, 2H), 3.95 (s, 1H).; ^{13}C NMR (101 MHz, CDCl$_3$) δ (ppm): 157.12, 154.78, 144.58 (d, J = 1.8 Hz), 139.34, 128.75, 127.48 (d, J = 17.8 Hz), 115.74 (d, J = 22.2 Hz), 113.72 (d, J = 7.4 Hz), 48.97; HRMS (EI+): m/z calcd for [C$_{13}$H$_{12}$FN]$^{+}$: 201.0954, found 201.0955.

4-Methoxy-N-(naphthalen-1-ylmethyl)aniline (3ja)

Yellow oil; ^{1}H NMR (400 MHz, CDCl$_3$) δ (ppm) : 8.07 (d, J = 7.1 Hz, 1 H), 7.89 (m, 1 H), 7.80 (d, J = 8.2 Hz, 1 H), 7.55 – 7.47 (m, 3 H), 7.45 – 7.38 (m, 1 H), 6.81 (d, J = 8.9 Hz, 2 H), 6.65 (d, J = 8.9 Hz, 2 H), 4.69 (s, 2 H), 3.75 (s, 4H, including an NH); ^{13}C NMR (101 MHz, CDCl$_3$) δ (ppm): 152.31, 142.73, 134.76, 133.98,

131.68, 128.88, 128.23, 126.41, 126.13 , 125.93, 125.67, 123.74, 115.08, 114.07, 55.98, 47.43; HRMS (EI$^+$): m/z calcd for [C$_{14}$H$_{15}$N]$^+$: 197.1204, found 197.1205; HRMS (EI+): m/z calcd for [C$_{18}$H$_{17}$NO]$^+$: 263.1310, found 263.1308.

N-Isopropyl-4-methoxyaniline (3ja)

Yellow oil; ^{1}H NMR (400 MHz, CDCl$_3$) δ (ppm) : 6.77 (d, J = 8.8 Hz, 2 H), 6.56 (d, J = 8.8 Hz, 2 H), 3.74 (s, 3 H), 3.54 (m, 1 H), 3.06 (s, 1 H), 1.18 (d, J = 6.3 Hz, 6 H); ^{13}C NMR (101 MHz, CDCl$_3$) δ (ppm): 152.06, 141.89, 115.04, 55.94, 45.36, 23.23; HRMS (EI$^+$): m/z calcd for [C$_{10}$H$_{15}$NO]$^+$: 165.1154, found 165.1154.

N-(sec-Butyl)-4-methoxyaniline (3la)

Yellow oil; ^{1}H NMR (400 MHz, CDCl$_3$) δ (ppm) : 6.77 (d, J = 8.8 Hz, 2 H), 6.55 (d, J = 8.8 Hz, 2 H), 3.74 (s, 3 H), 3.41 – 3.26 (m, 1 H), 3.14 (s, 1 H), 1.58 (m, 1 H), 1.48 – 1.35 (m, 1 H), 1.14 (d, J = 6.3 Hz, 3 H), 0.94 (t, J = 7.4 Hz, 3 H); ^{13}C NMR (101 MHz, CDCl$_3$) δ (ppm): 151.89, 142.09, 115.06, 114.81, 55.96, 50.94, 29.78, 20.41, 10.50 ; HRMS (EI$^+$): m/z calcd for [C$_{11}$H$_{17}$NO]$^+$: 179.1310, found 179.1311.

N-Cyclohexyl-4-methoxyaniline (3ka)

White solid; m.p. = 44 ℃; ^{1}H NMR (400 MHz, CDCl$_3$) δ (ppm) : 6.76 (d, J = 8.8 Hz, 2 H), 6.57 (d, J = 8.8 Hz, 2 H), 3.73 (s, 3 H), 3.16 (m, 2 H including an NH), 2.13 – 1.95 (m, 2 H), 1.84 – 1.69 (m, 2 H), 1.64 (dd, J = 8.7, 3.8 Hz, 1 H), 1.44 – 1.28 (m, 2 H), 1.28

– 1.17 (m, 1 H), 1.17 – 1.03 (m, 2 H); ^{13}C NMR (101 MHz, CDCl$_3$) δ (ppm): 151.92, 141.72, 114.99, 114.89, 55.89, 52.86, 33.72, 26.09, 25.18; HRMS (EI$^+$): m/z calcd for [C$_{13}$H$_{19}$NO]$^+$: 205.1467, found 205.1469.

N–Butyl–4–methoxyaniline (3ma)

Yellow oil; ^{1}H NMR (400 MHz, CDCl$_3$) δ (ppm) : 6.78 (d, J = 8.9 Hz, 2 H), 6.58 (d, J = 8.9 Hz, 2 H), 3.74 (s, 3 H), 3.32 (s, 1 H), 3.11 – 3.01 (m, 2 H), 1.59 (dt, J = 14.4, 6.9 Hz, 2 H), 1.42 (dq, J = 14.4, 7.3 Hz, 2 H), 0.95 (t, J = 7.3 Hz, 3 H); ^{13}C NMR (101 MHz, CDCl$_3$) δ (ppm): 152.06, 143.02, 115.02, 114.12, 55.97, 44.82, 31.93, 20.46, 14.08; HRMS (EI$^+$): m/z calcd for [C$_{11}$H$_{17}$NO]$^+$: 179.1310, found 179.1313.

Dibenzylamine (3ac)

Colorless oil; ^{1}H NMR (400 MHz, CDCl$_3$) δ (ppm): 7.38 – 7.29 (m, 8 H), 7.27 – 7.21 (m, 2 H), 3.81 (s, 4 H), 1.61 (s, 1 H); ^{13}C NMR (101 MHz, CDCl$_3$) δ (ppm): 140.48, 128.52, 128.27, 127.06, 53.31; HRMS (EI$^+$): m/z calcd for [C$_{14}$H$_{15}$N]$^+$: 197.1204, found 197.1203.

Tribenzylamine (3ad)

White solid; m.p. = 93 ℃; ^{1}H NMR (400 MHz, CDCl$_3$) δ (ppm): 7.49 (d, J = 7.3 Hz, 6 H), 7.39 (t, J = 7.5 Hz, 6 H), 7.29 (t, J = 7.2 Hz, 3 H), 3.63 (s, 6 H); ^{13}C NMR (101 MHz, CDCl$_3$) δ (ppm): 139.76, 128.85, 128.34, 126.98, 58.04; HRMS (EI$^+$): m/z calcd for

$[C_{21}H_{21}N]^+$: 287.1674, found 287.1671.

N,N-Dibenzylbutan-1-amine (3a'e)

Colorless oil; ^{1}H NMR (400 MHz, CDCl$_3$) δ (ppm): 7.36 (d, J = 7.6 Hz, 4 H), 7.30 (dd, J = 9.9, 5.2 Hz, 4 H), 7.25 – 7.18 (m, 2 H), 3.54 (s, 4 H), 2.48 – 2.31 (m, 2 H), 1.49 (dt, J = 14.8, 7.3 Hz, 2 H), 1.29 (dq, J = 14.6, 7.2 Hz, 2 H), 0.82 (dd, J = 7.6, 7.0 Hz, 3 H); ^{13}C NMR (101 MHz, CDCl$_3$) δ (ppm): 140.23, 128.87, 128.23, 126.80, 58.39, 53.29, 29.39, 20.59, 14.19; HRMS (EI$^+$): m/z calcd for $[C_{18}H_{23}N]^+$: 253.1830, found 253.1829.

N,N-Dibenzyl-4-methoxyaniline (3a'a)

White solid; m.p. = 85 ℃; ^{1}H NMR (400 MHz, CDCl$_3$) δ (ppm): 7.30 (m, 4 H), 7.27 – 7.20 (m, 6 H), 6.78 – 6.72 (m, 2 H), 6.71 – 6.66 (m, 2 H), 4.55 (s, 4 H), 3.70 (s, 3 H); ^{13}C NMR (101 MHz, CDCl$_3$) δ (ppm): 151.77, 143.89, 139.09, 128.66, 127.00, 126.93, 114.82, 114.57, 55.81, 55.23; HRMS (EI$^+$): m/z calcd for $[C_{21}H_{21}NO]^+$: 303.1623, found 303.1621.
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N-Benzyl-4-methoxy-N-(4-methoxybenzyl)aniline (3bl)

Colorless oil; ^{1}H NMR (400 MHz, CDCl$_3$) δ (ppm): 7.30 (m, 2 H), 7.27 – 7.21 (m, 3 H), 7.19 – 7.13 (m, 2 H), 6.85 (m, 2 H), 6.76 (m, 2 H), 6.73 – 6.67 (m, 2 H), 4.52 (s, 2 H), 4.49 (s, 2 H), 3.79 (s, 3 H), 3.73 (s, 3 H); ^{13}C NMR (101 MHz, CDCl$_3$) δ (ppm): 158.67, 151.81, 144.00, 139.18, 130.94, 128.63, 128.25, 127.07, 126.89,

114.86, 114.81, 114.06, 55.83, 55.39, 55.10, 54.72; HRMS (EI$^+$): m/z calcd for [C$_{23}$H$_{23}$NO$_2$]$^+$: 333.1729, found 333.1729.

N-Benzylbutan-1-amine (3ae)

Colorless oil; ^{1}H NMR (500 MHz, CDCl$_3$) δ (ppm): 7.43 – 7.22 (m, 5 H), 3.82 (d, J = 1.7 Hz, 2 H), 2.73 – 2.59 (m, 2 H), 1.60 – 1.47 (m, 2 H), 1.39 (m, 2 H), 1.01 – 0.90 (m, 3 H); ^{13}C NMR (126 MHz, CDCl$_3$) δ (ppm): 140.74, 128.45, 128.19, 126.92, 54.25, 49.33, 32.39, 20.61, 14.14; HRMS (EI$^+$): m/z calcd for [C$_{11}$H$_{17}$N]$^+$: 163.1361, found 163.1362.

N-Benzyl-N-butyl-1-butanamine (3af)

Yellow oil; ^{1}H NMR (400 MHz, CDCl$_3$) δ (ppm): 7.37 – 7.27 (m, 4 H), 7.23 (m, 1 H), 3.55 (s, 2 H), 2.46 – 2.37 (m, 4 H), 1.53 – 1.41 (m, 4 H), 1.31 (dq, J = 14.3, 7.2 Hz, 4 H), 0.89 (t, J = 7.3 Hz, 6 H); ^{13}C NMR (101 MHz, CDCl$_3$) δ (ppm): 140.38, 128.77, 128.01, 126.52, 58.63, 53.55, 29.28, 20.62, 14.09; HRMS (EI$^+$): m/z calcd for [C$_{15}$H$_{25}$N]$^+$: 219.1987, found 219.1984.

4-methoxy-N-(phenylmethylene)-benzenamine (4aa)

Yellow solid; m.p. = 65℃; ^{1}H NMR (400 MHz, CDCl$_3$) δ (ppm): 8.47 (s, 1H), 7.95 – 7.82 (m, 2H), 7.49 – 7.42 (m, 3H), 7.23 (d, J = 9.0 Hz, 2H), 6.92 (d, J = 8.7 Hz, 2H), 3.82 (s, 3H).; ^{13}C NMR (101 MHz, CDCl$_3$) δ (ppm): 158.33, 158.26, 144.92, 136.45, 130.96, 128.68, 128.54, 122.14, 114.36, 55.46.

2－Phenylisoindolin－1－one (4a)

White solid; m.p. = 163 ℃; ^{1}H NMR (500 MHz, CDCl$_3$) δ (ppm)：7.92 (d, J = 7.3 Hz, 1 H), 7.87 (d, J = 7.9 Hz, 2 H), 7.58 (d, J = 7.2 Hz, 1 H), 7.51 (d, J = 7.6 Hz, 2 H), 7.42 (t, J = 7.5 Hz, 2 H), 7.17 (s, 1 H), 4.84 (s, 2 H); ^{13}C NMR (126 MHz, CDCl$_3$) δ (ppm)：167.46, 140.13, 139.49, 133.19, 132.05, 129.12, 128.32, 124.39, 124.03, 122.64, 119.35, 50.66; HRMS (EI$^+$): m/z calcd for [C$_{14}$H$_{11}$NO]$^+$: 209.0841, found 209.0840.

2－(p－Tolyl)isoindolin－1－one (4b)

White solid; m.p. = 140 ℃; ^{1}H NMR (400 MHz, CDCl$_3$) δ (ppm)：7.90 (d, J = 7.5 Hz, 1 H), 7.72 (d, J = 8.2 Hz, 2 H), 7.61 – 7.54 (m, 1 H), 7.48 (d, J = 5.5 Hz, 2 H), 7.20 (d, J = 8.1 Hz, 2 H), 4.78 (s, 2 H), 2.33 (s, 3 H); ^{13}C NMR (101 MHz, CDCl$_3$) δ (ppm)：167.43, 140.23, 137.05, 134.22, 133.42, 131.98, 129.74, 128.38, 124.11, 122.67, 119.62, 50.91, 20.96; HRMS (EI$^+$): m/z calcd for [C$_{15}$H$_{13}$NO]$^+$: 223.0997, found 223.0996.

2－(4－Methoxyphenyl)isoindolin－1－one (4c)

Yellow solid; m.p. = 135 ℃; ^{1}H NMR (400 MHz, CDCl$_3$) δ (ppm)：7.89 (d, J = 7.9 Hz, 1 H), 7.72 (dd, J = 8.9, 1.8 Hz, 2 H), 7.56 (dd, J = 9.7, 4.1 Hz, 1 H), 7.52 – 7.43 (m, 2 H), 6.94 (dd, J = 8.9, 1.7 Hz, 2 H), 4.77 (s, 2 H), 3.80 (s, 3 H); ^{13}C NMR (101 MHz, CDCl$_3$) δ (ppm)：167.18, 156.54, 140.10, 133.23, 132.61, 131.76, 128.25,

123.94, 122.53, 121.38, 114.27, 55.45, 51.10; HRMS (EI$^+$): m/z calcd for [C$_{15}$H$_{13}$NO$_2$]$^+$: 239.0946, found 239.0946.

2-(4-Chlorophenyl)isoindolin-1-one (4d)

White solid; m.p. = 181 ℃; ^{1}H NMR (400 MHz, CDCl$_3$) δ (ppm)：7.88 (d, J = 7.9 Hz, 1 H), 7.81 (d, J = 8.7 Hz, 2 H), 7.58 (t, J = 7.4 Hz, 1 H), 7.49 (d, J = 6.8 Hz, 2 H), 7.35 (d, J = 8.7 Hz, 2 H) , 4.79 (s, 2 H); ^{13}C NMR (101 MHz, CDCl$_3$) δ (ppm): 167.45, 139.83, 138.06, 132.87, 132.27, 129.45, 129.10, 128.47, 124.15, 122.61, 120.33, 50.58; HRMS (EI$^+$): m/z calcd for [C$_{14}$H$_{10}$ClNO]$^+$: 243.0451, found 243.0449.

4-(Benzylamino)phenyl acetate (3al)

Yellow solid; m.p. = 57 ℃; ^{1}H NMR (400 MHz, CDCl$_3$) δ (ppm): 7.37 – 7.23 (m, 5 H), 6.88 (d, J = 9.0 Hz, 2 H), 6.58 (d, J = 9.0 Hz, 2 H), 4.28 (s, 2 H), 4.04 (s, 1 H), 2.24 (s, 3 H); ^{13}C NMR (101 MHz, CDCl$_3$) δ (ppm): 170.32, 146.14, 142.12, 139.29, 128.72, 127.54, 127.35, 122.16, 113.23, 48.65, 21.16; HRMS (EI$^+$): m/z calcd for [C$_{15}$H$_{15}$NO$_2$]$^+$: 241.1103, found 241.1104.

N-Benzylnaphthalen-1-amine (3am)

Yellow solid; m.p. = 67 ℃; ^{1}H NMR (400 MHz, CDCl$_3$) δ (ppm)：7.86 – 7.72 (m, 2 H), 7.51 – 7.13 (m, 9 H), 6.61 (d, J = 7.4 Hz, 1 H), 4.67 (s, 1 H), 4.48 (s, 2 H); ^{13}C NMR (101 MHz, CDCl$_3$) δ (ppm): 143.33, 139.22, 134.41, 128.85, 128.82, 127.86, 127.52, 126.74, 125.87, 124.88, 123.49, 120.01, 117.75, 104.85, 48.73;

HRMS (EI$^+$): m/z calcd for [C$_{17}$H$_{15}$N]$^+$: 233.1204, found 233.1203.

1-(4-Methoxyphenyl)-2,5-dimethyl-1H-pyrrole (5)

White solid; m.p. = 61 ℃; ^{1}H NMR (400 MHz, CDCl$_3$) δ (ppm): δ 7.05 (d, J = 8.9 Hz, 2H), 6.89 (d, J = 8.9 Hz, 2H), 5.80 (s, 2H), 3.78 (s, 3H), 1.94 (s, 6H); ^{13}C NMR (101 MHz, CDCl$_3$) δ (ppm): 158.85, 131.74, 129.21, 129.00, 114.19, 105.26, 55.44, 12.96; HRMS (EI$^+$): m/z calcd for [C$_{13}$H$_{15}$NO]$^+$: 201.1154, found 201.1152.

Quinoline (6)

Yellow oil; ^{1}H NMR (400 MHz, CDCl$_3$) δ (ppm) : 8.95 – 8.81 (m, 1 H), 8.12 (d, J = 8.5 Hz, 1 H), 8.03 (d, J = 8.3 Hz, 1 H), 7.72 (d, J = 8.2 Hz, 1 H), 7.69 – 7.62 (m, 1 H), 7.46 (dd, J = 8.1, 7.0 Hz, 1 H), 7.28 (dd, J = 8.3, 4.2 Hz, 1 H); ^{13}C NMR (101 MHz, CDCl$_3$) δ (ppm): 149.86, 147.76, 135.45, 128.93, 128.90, 127.73, 127.27, 125.98, 120.52; HRMS (EI$^+$): m/z calcd for [C$_9$H$_7$N]$^+$: 129.0578, found 129.0579.

Reference

(1) For recent papers, see: (a) Xu, Z.; Yan, P.; Xu, W.; Jia, S.; Xia, Z.; Chung, B.; Zhang, Z. C. *RSC Adv.* **2014**, *4*, 59083−59087. (b) Zhu, M. *Catal. Lett.* **2014**, *144*, 1568−1572. (c) Zhou, S.; Fleischer, S.; Jiao, H.; Junge, K.; Beller, M. *Adv. Synth. Catal.* **2014**, *356*, 3451−3455.

(2) For organocatalytic reductive amination using Brønsted acids in combination with a Hantzsch ester, see: (a) Storer, R. I.; Carrera, D. E.; Ni Y.; Macmillan, D. W. C. *J. Am. Chem. Soc.* **2006**, *128*, 84−86. (b) Zhou, J.; List, B. *J. Am. Chem. Soc.* **2007**, *129*, 7498−7499. For biocatalytic reductive amination, see: (c) Koszelewski, D.; Lavandera, I.; Clay, D.; Guebitz, G. M.; Rozzell D.; Kroutil, W. *Angew. Chem., Int. Ed.* **2008**, *47*, 9337−9340. For hydrogen transfer in reductive amination, see: (d) Williams, G. D.; Pike, R. A.; Wade C. E.; Wills, M. *Org. Lett.* **2003**, *5*, 4227−4230. (e) Kadyrov R.; Riermeier, T. H. *Angew. Chem., Int. Ed.* **2003**, *42*, 5472−5474. For asymmetric reductive aminations catalyzed by transition metals, see: (f) Chi, Y.; Zhou Y. G.; Zhang, X. *J. Org. Chem.* **2003**, *68*, 4120−4122. (g) Kadyrov, R.; Riermeier, T. H.; Dingerdissen, U.; Tararov

V.; Börner, A. *J. Org. Chem.* **2003**, *68*, 4067−4070. (h) Chang, M.; Liu, S.; Huang K.; Zhang, X. *Org. Lett.* **2013**, *15*, 4354−4357.

(3) For hydrogenation, see: (a) Pagnoux−Ozherelyeva, A.; Pannetier, N.; Mbaye, M. D.; Gaillard, S.; Renaud, J.−L. *Angew. Chem., Int. Ed.* **2012**, *51*, 4976. (b) Nasrollahzadeh, M. *New J. Chem.* **2014**, *38*, 5544−5550. For hydride reducing, see: (c) R. F. Borch, M. D. Bernstein, H. D. Durst, *J. Am. Chem. Soc.* **1971**, *93*, 2897−2904. (d) Sato, S.; Sakamoto, T.; Miyazawa, E.; Kikugawa, Y. *Tetrahedron* **2004**, *60*, 7899−7906.

(4) (a) Kadyrov, R.; Riermeier, T. H. *Angew. Chem., Int. Ed.* 2003, *42*, 5472−5474. (b) Wang, C.; Pettman, A.; Basca, J.; Xiao, J. *Angew. Chem., Int. Ed.* **2010**, *49*, 7548−7552. (c) Wei, Y.; Wang, C.; Jiang, X.; Xue, D.; Li, J.; Xiao, J. *Chem. Commun.* **2013**, *49*, 5408−5410. (d) Talwar, D.; Salguero, N. P.; Robertson, C. M.; Xiao, J. *Chem. Eur. J.* **2014**, *20*, 245−252.

(5) Chusov, D.; List, B. *Angew. Chem., Int. Ed.* **2014**, *53*, 5199−5201.

(6) Iqbal, A. F. M. *Tetrahedron Letters* **1971**, *12*, 37, 3385–3388.

(7) (a) Astruc, D.; Lu, F.; Aranzaes, J. R. *Angew. Chem., Int. Ed.* **2005**, *44*, 7852−7872. (b) Yan, N.; Xiao, C.; Kou, Y. *Coord. Chem.*

Rev. **2010**, *254*, 1179–1218. (c) Shylesh, S.; Schnemann, V.; Thiel, W. R. *Angew. Chem., Int. Ed.* **2010**, *49*, 3428–3459. (d) Polshettiwar, V.; Luque, R.; Fihri, A.; Zhu, H.; Bouhrara, M.; Basset, J.-M. *Chem. Rev.* **2011**, *111*, 3036–3075.

(8) (a) Park, K. H.; Son, S. U.; Chung, Y. K. *Chem. Commun.* **2003**, 1898–1899. (b) Park, K. H.; Son, S. U.; Chung, Y. K. *Org. Lett.* **2002**, *4*, 4361–4363.

(9) (a) Park, J. H.; Chung, Y. K. *Dalton Trans.* **2008**, 2369–2378. (b) Park, J. H.; Kim, S. Y.; Chung, Y. K. *Synlett* **2007**, 453–459.

(10) Park, J. H.; Kim, E.; Chung, Y. K. *Org. Lett.* **2008**, *10*, 4719–4721.

(11) Gülak, S.; Wu, L.; Liu, Q.; Franke, R.; Jackstell, R.; Beller, M. *Angew. Chem., Int. Ed.* **2014**, *53*, 7320–7323.

(12) For Ru, see: Kolesnikov, P. N.; Yagafarov, N. Z.; Usanov, D. L.; Maleev, V. I.; Chusov, D. *Org. Lett.* **2015**, *17*, 173–175.

(13) (a) Knifton, J. F. *J. Org. Chem.* **1976**, *41*, 1200–1206. (b) Harsy, S. G. *Tetrahedron* **1990**, *46*, 7403–7412. (c) Blaser, H. U.; Steiner, H.; Studer, M. *ChemCatChem* **2009**, *1*, 210–221. (d) Kim, J. H.; Park, J. H.; Chung, Y. K. *Adv. Synth. Catal.* **2012**, *354*, 2412–2418.

(14) (a) Cann, K.; Cole, T.; Selegeir, W.; Pettit, R. *J. Am. Chem. Soc.* **1978**, *100*, 3969−3969. (b) Kaneda, K.; Hiraki, M.; Imanaka, T.; Teranishi, S. *J. Mol. Catal.* **1981**, 385−387. (c) Watanabe, Y.; Tsuji, Y.; Ohsumi, T.; Takeuchi, R. *Tetrahedron Lett.* **1983**, *24*, 4121−4122. (d) Shvo, Y.; Czarkie, D. *J. Organomet. Chem.* **1989**, *368*, 357−365. (e) Liu, L.; Qiao, B.; Chen, Z.; Zhang, J.; Deng, Y. *Chem. Commun.* **2009**, 653−655.

(15) (a) Sreedhar, B.; Reddy, P. S.; Devi, D. K. *J. Org. Chem.* **2009**, *74*, 8806−8809. (b) Tang, C.-H.; He, L.; Liu, Y.-M.; Cao, Y.; He, H.-Y.; Fan, K.-N. *Chem. Eur. J.* **2011**, *17*, 7172−7177. (c) Li, L.; Niu, Z.; Cai, S.; Zhi, Y.; Li, H.; Rong, H.; Liu, L.; Liu, L.; He, W.; Li, Y. *Chem. Commun.* **2013**, *49*, 6843−6845. (d) Stemmler, T.; Westerhaus, F. A.; Surkus, A.-E.; Pohl, M.-M.; Junge, K.; Beller, M. *Green Chem.* **2014**, *16*, 4535−4540.

(16) Lei, Q.; Wei, Y.; Talwar, D.; Wang, C.; Xue, D.; Xiao, J. *Chem. Eur. J.* **2013**, *19*, 4021−4029.

(17) Dombray, T.; Helleu, C.; Darcel, C.; Sortais, J.-B. *Adv. Synth. Catal.* **2013**, *355*, 3358−3362.

(18) Lu, S.; Wang, J.; Cao, X.; Li, X.; Gu, H. *Chem. Commun.* **2014**, *50*, 3512−3515.

(19) Cui, X.; Dai, X.; Deng, Y.; Shi, F. *Chem. Eur. J.* **2013**, *19*, 3665–3675.

(20) Satyanarayana, P.; Reddy, G. M.; Maheswaran, H.; Kantam, M. L. *Adv. Synth. Catal.* **2013**, *355*, 1859–1867.

(21) Zheng, J.; Roisnel, T.; Darcel, C.; Sortais, J.-B. *ChemCatChem* **2013**, *5*, 2861–2864.

(23) Roman, G. *J. Serb. Chem. Soc.* **2012**, *77*, 131–140.

(24) Chusov, D.; List, B. *Angew. Chem. Int. Ed.* **2014**, *53*, 5199–5201.

(25) Zhu, X.; Su, L.; Huang, L.; Chen, G.; Wang, J.; Song, H.; Wan, Y. *Eur. J. Org. Chem.* **2009**, 635–642.

(26) Menche, D.; Böhm, S.; Li, J.; Rudolph, S.; Zander, W. *Tetrahedron Lett.* **2007**, *48*, 365–369.

(27) Yoshikai, N.; Mieczkowski, A.; Matsumoto, A.; Illies, L.; Nakamura, E. *J. Am. Chem. Soc.* **2010**, *132*, 5568–5569.

(28) Han, L.; Xing, P.; Jiang, B. *Org. Lett.* **2014**, *16*, 3428–3431.

(29) Shi, L. Y.; Wang, J. Q.; Cao, Q. X.; Gu, H. W. *Org. Lett.* **2012**, *14*, 1876–1879.

(30) Banik, B. K.; Samajdar, S.; Banik, I. *J. Org. Chem.* **2004**, *69*, 213–216.

(31) Flanagan, J. C. A.; Dornan, L. M.; McLaughlin, M. G.; McCreanor, N. G.; Cook, M. J.; Muldoon, M. J. *Green Chem.* **2012**, *14*, 1281−1283.

(32) Park, J. H.; Kim, E.; Chung, Y. K. *Org. Lett.* **2008**, *10*, 4719−4721.

국문초록

외부 수소원 없이 5기압의 일산화탄소와 물 존재하에 탄소에 담지된 코발트-로듐 헤테로금속 나노입자 촉매를 사용하는 알데하이드 및/또는 케톤과 아민 및/또는 나이트로아렌의 환원성 아민화 반응을 개발하였다. 이 반응은 반응계 내에서 생성된 물과 일산화탄소가 수성 가스 반응을 일으켜 만들어진 수소를 사용한다. 이 촉매는 반응조건에서 안정하고 8번 재사용시에도 촉매활성을 유지하였다.

주요어: 불균일 촉매반응, 아민화, 환원반응, 일산화탄소, 물

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