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Allylic amination of unfunctionalyzed olefins by nitroarenes and CO, catalyzed by $Ru_3(CO)_{12}$/Ph-BIAN (Ph-BIAN=bis(phenylimino)acenaphthenequinone): extension to the synthesis of allylic amines with strongly electron-withdrawing or electron-donating groups on the aryl ring

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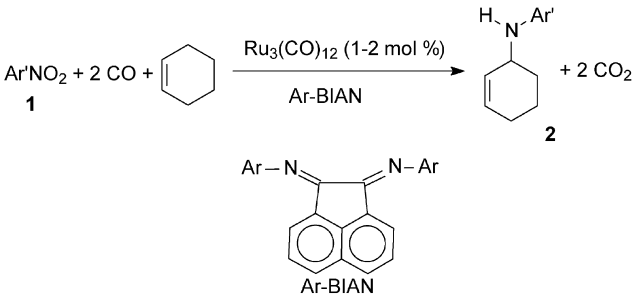
Abstract—The allylic amination of unfunctionalyzed olefins by nitroarenes under CO pressure, catalyzed by $Ru_3(CO)_{12}$/Ph-BIAN (Ph-BIAN=bis(phenylimino)acenaphthenequinone) has been extended to some substrates with strongly electron-withdrawing groups on the nitroarene. Reaction of 1,4-dinitrobenzene selectively affords functionalization of only one nitro group, the other remaining unreacted. However, the second nitro group can be reduced in one pot by CO/H_2O in the presence of the same catalytic system employed in the amination reaction, to afford the corresponding 4-amino derivative. Some attempts to render the reaction enantioselective by employing chiral bis-oxazolines as ligands in place of Ph-BIAN are described. Bis-oxazolines are suitable ligands for the reaction, although not as efficient as Ph-BIAN, but the allylic amine obtained was found to be racemic.

1. Introduction

Allylic amines are important building blocks or final products in organic chemistry and much attention has been devoted to their synthesis.[1] The most often employed synthetic method involves nucleophilic attack of an amine on a π-allyl complex. This is in turn generated by reaction of a suitable metal complex with a prefunctionalized allylic compound, such as an acetate or an halide. The method often gives high yields, but has two limitations. The first is that a prefunctionalized substrate is required, which often needs preliminary steps to be prepared. The second is that the amine must be nucleophilic enough to react with the complex and aromatic amines having electron-withdrawing substituents on the aryl ring are generally poor substrates in these reactions. Some years ago, we reported on a new synthetic way to produce allylic amines, employing a simple unactivated olefin, cyclohexene, and an aromatic nitro compound as the aminating reagent, under reducing conditions (CO pressure). Although the method requires the use of a high-pressure apparatus, the reagents are bulk, cheap commercial products which do not need to be purified (although an higher selectivity can be achieved by purifying the olefin), the experimental operations are simple, the selectivity was high (up to 81.9%), and the turnover numbers were higher than those reported for most C–H activation reactions (Scheme 1).[2–4]



Scheme 1.

One feature of this reaction, which is interesting in view of what said above, apart from the fact of producing CO_2 as the only stoichiometric byproduct, is that nitroarenes bearing electron-withdrawing substituents were those where the highest selectivities were obtained. In this work we have extended the range of nitroarenes for which the reaction may be performed, employing substrates having strongly electron-withdrawing groups on the nitroarene.

Keywords: Allylic amines; Nitroarenes; Carbonylation reactions; Ruthenium; Imines.
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Despite the good results obtained with nitroarenes having electron-withdrawing substituents, substrates with strong electron-donating groups such as methoxy or amino are not suitable substrates for amination reactions of this kind. We have now found a two step-one pot procedure to the 4-amino derivative in good yields. The amino group can be an important entry to a variety of other derivatives. Some preliminary attempts to make the reaction enantioselective are further described.

2. Results and discussion

2.1. Nitroarenes with strongly electron-withdrawing substituents

Four nitroarenes bearing strong electron-withdrawing substituents were employed in this work, 4-$MeOC(O)C_6H_4NO_2$ (**1a**), 3,5-$Cl_2C_6H_3NO_2$ (**1b**), 3,5-$(CF_3)_2C_6H_3NO_2$ (**1c**), and 4-$O_2NC_6H_4NO_2$ (**1d**), none of which has been previously employed in these reactions. The last contains two nitro groups both of which may in principle react. However, we had previously observed that the presence of the strong electron-donating 4-methoxy group on the aryl ring of the nitroarene led to a very slow reaction.[2–4] After one of two nitro groups has reacted, it is converted into an even more electron-releasing amino group. Thus, we deemed a selective reaction of only one nitro group could be feasible.

The results of a series of reactions run under previously optimized conditions (T=160 °C, P_{CO}=40 bar, mol ratios $ArNO_2$/Ph-BIAN/$Ru_3(CO)_{12}$=50:3.75:1)[3] are reported in Table 1. Good selectivities were obtained in all cases and the 84% selectivity in the allylic amine bearing the fluorinated groups is the highest obtained to date in these reactions. As expected, only mono-functionalization was observed for dinitrobenzene and no byproducts were observed in which the second nitro group had been transformed in any way.

When using 4-$MeO_2CC_6H_4NO_2$ as substrate by lowering the temperature a very low conversion results, but with the more reactive 3,5-$(CF_3)_2C_6H_3NO_2$ substrate a significant reaction was observed even at 100 °C.

The only observable byproduct was the aniline corresponding to the nitroarene employed, but small amounts of the corresponding diarylureas are probably also formed, which could not be detected by gas-chromatography. We have previously shown that the hydrogen atoms necessary for the aniline formation come from a ruthenium-catalyzed dehydrogenation of cyclohexene to afford cyclohexadiene and benzene.[3]

Although a complete purification of the allylic amines required chromatography on silica, almost pure samples could be obtained by subsequent acidic extraction with HCl at different concentrations (see Section 4 for details). Indeed, the byproduct anilines are extracted easily into 1 M aqueous HCl, whereas the allylic amines require a more concentrated acid and the presence of methanol as a co-solvent.

2.2. Synthesis of *N*-cyclohex-2-enyl-benzene-1,4-diamine (2e)

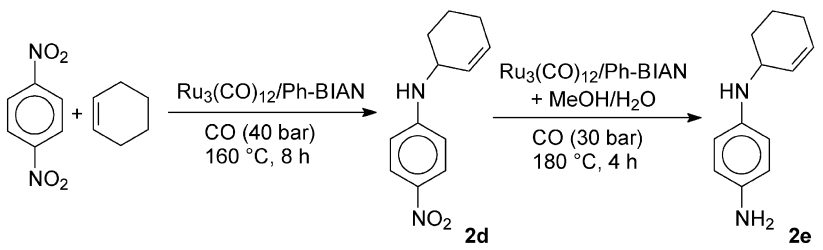
As alluded to in the introduction, the main limit of this type of reaction discussed in this paper is that when it is applied to nitroarenes bearing strongly electron-donating substituents, only very low conversions and selectivities are observed. The reason for this is two-fold. First, the evidence accumulated indicates that the initial reduction of the nitroarene always proceeds by a single electron transfer from the complex to the nitroarene and this is disfavored by electron-donating substituents on the nitroarene.[5] Moreover, coupling between the olefin and the nitrogen-containing complex occurs by a metal catalyzed ene reaction between the olefin and the intermediately formed nitrosoarene and this is also disfavored by the same donating substituents.[1,6] Use of a free amino group in a nitroaniline would further complicate the issue, since the amino group may enter the reaction via an alternative pathway, to yield diarylureas.[5] A different catalytic system, reported by Nicholas for the same reactions, suffers from the same limitations.[7]

Molecules having free amino groups are important both as such and because the amino group can be easily functionalized or transformed (e.g. via an azonium salt) into many other groups. Thus it would be interesting to prepare them by our methodology. The system $Ru_3(CO)_{12}$/Ar-BIAN is also the most active catalyst known to date for the reduction of nitroarenes to anilines by CO/H_2O.[8,9] This reaction proceeds much more easily than the amination reaction and the presence of an electron-donating substituent on the nitroarene is not a major problem here. Since we have now been able to synthesize the 4-nitro derivative **2d**, we effected a two step-one pot reaction from dinitrobenzene. In the first step, **2d** is produced under the

Table 1. Synthesis of allylamines **2** from cyclohexene and different nitroarenes[a]

Run	$Ru_3(CO)_{12}$ (mmol)	Cyclohexene (mL)	Nitroarene	Nitroarene conversion (%)[b]	Allylamine select (%)[c]	Aniline select (%)[c]
1	0.0306	30	3,5-$Cl_2C_6H_3NO_2$ (**1b**)	99.1	57.2 (**2b**)	12.0
2	0.0306	30	4-$MeO_2CC_6H_4NO_2$ (**1a**)	100	42.1 (**2a**)	10.4
3	0.0306	30	1,4-$(NO_2)_2C_6H_4$ (**1d**)	100	52.7(**2d**)	3.2
4	0.0102	10	3,5-$(F_3C)_2C_6H_3NO_2$ (**1c**)	99.9	83.1 (**2c**)	14.4
5[d]	0.0102	10	3,5-$(F_3C)_2C_6H_3NO_2$ (**1c**)	41.9	84.3 (**2c**)	15.7
6[e]	0.0102	10	3,5-$(F_3C)_2C_6H_3NO_2$ (**1c**)	39.7	52.3 (**2c**)	32.8

[a] Experimental conditions: mol ratios $ArNO_2$/Ph-BIAN/$Ru_3(CO)_{12}$=50:3.75:1, T=160 °C, P_{CO}=40 bar, t=6 h.
[b] Calculated with respect to the starting nitroarene by GC analysis (naphthalene as an internal standard).
[c] Calculated with respect to the converted nitroarene by GC analysis (naphthalene as an internal standard).
[d] T=130 °C.
[e] T=100 °C.



Scheme 2.

same conditions reported in this paper (Table 1). Then the autoclave was opened and water and methanol (to improve miscibility) were added. The autoclave was charged again with CO and the reaction run under the temperature and pressure conditions previously shown to give a 99% selectivity in the reduction of nitrobenzene to aniline (Scheme 2).[9]

At the end of the reaction, **2d** had been completely consumed to afford the corresponding amine **2e**. The total selectivity in **2e** (52.8%) is indistinguishable within experimental error from the one in **2d** in the single step reaction, indicating that the reduction step occurs in essentially quantitative yields.

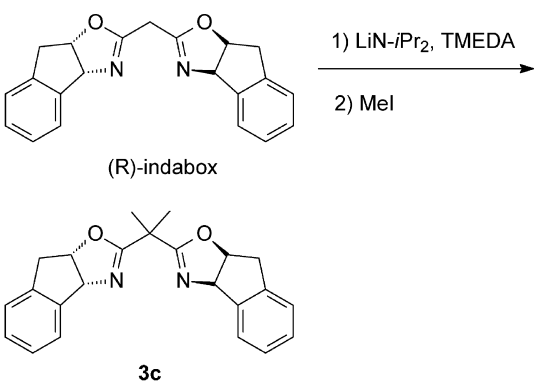
It should be noted that any amination procedure based on a reaction of 1,4-diaminobenzene with a functionalized substrate would surely have to face the problem of multiple substitution not only on the same nitrogen atom, but even on the second one, so that up to four products can be expected, differing in the alkylation extent. On the other hand, with our strategy only the monosubstituted product can be obtained.

During the reaction a small amount of unsubstituted aniline was formed, whose origin is uncertain. Another independent product was formed (as evidenced by GC-MS analysis), which does not include the nitroarene-derived fragment, CyCOOMe. This ester clearly derives from the carboxylation reaction of cyclohexene, which is still present in the reaction mixture in large amount, by CO and methanol. When the reaction was performed by employing ethanol in place of methanol, the reduction reaction proceeded in the same way and CyCOOEt was formed in place of the corresponding methyl ester. This type of carboxylation reactions are typically catalyzed by palladium complexes. By searching through the literature we could only find two examples, both in the patent literature, for ruthenium-catalyzed olefin carboxylation reactions and in none of these examples was a nitrogen ligand present.[10,11] Since this reaction was outside the scope of the present paper, it was not investigated further at the moment, although it surely deserves attention.

2.3. Use of chiral bis-oxazolines as ligands

Given the importance chiral allylic amines have in pharmaceutical chemistry, we attempted to make our reaction asymmetric by employing a chiral ligand. Since no chiral Ar-BIAN has to date been reported, we decided to use bis-oxazolines as ligands. The choice was motivated by the fact that some years ago we employed similar, although not chiral, ligands in the $Ru_3(CO)_{12}$-catalyzed reduction of nitrobenzene to aniline by CO/H_2O with good results.[12] In the same work, we had noticed that the central $-CH_2-$ moiety of the bis-oxazoline had to be protected by alkylation in order for the catalyst to be active. The ligands employed in this work are shown in Scheme 3.

Two of these, **3a**,**b**, are commercially available, whereas the methylated indabox **3c** is not. Its synthesis from indandiol and dimethylmalononitrile in a low yield has been briefly reported in a communication,[13] but the experimental details and the characterization of the product were not reported. We preferred to start from the commercially available (*R*)-indabox ([3a*R*-[2(3′a*R* *,8′a*S* *),3′aβ,8′aβ]]-(+)-2,2′-methylenebis[3a,8a-dihydro-8*H*-indeno[1,2-*d*]oxazole) and we effected the methylation by deprotonation of the parent ligand by lithium diisopropylamide, followed by reaction with methyl iodide (Eq. (1)). The procedure is a modification of the one reported in the literature for the alkylation of the same or of related bis-oxazolines[14,15] and afforded pure **3c** in a 56.2% isolated yield.



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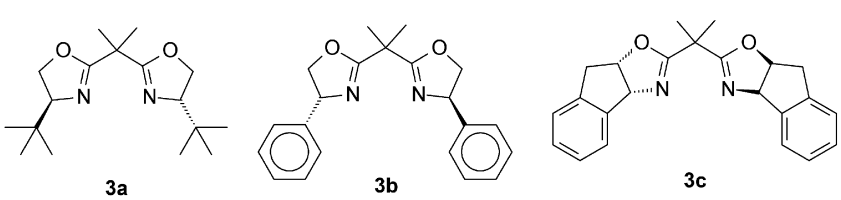

Scheme 3.

Table 2. Use of bis-oxazolines **3** as ligands[a]

Run	Ligand	T (°C)	t (h)	Nitroarene	Nitroarene conversion (%)[b]	Allylamine select (%)[c]	Aniline select (%)[c]
1	**3c**	160	6	4-$MeO_2CC_6H_4NO_2$	80.9	1.9 (**2a**)	3.0
2	**3b**	160	6	4-$MeO_2CC_6H_4NO_2$	56.4	8.0 (**2a**)	7.0
3	**3a**	160	6	4-$MeO_2CC_6H_4NO_2$	53.4	5.9 (**2a**)	13.6
4	**3a**	130	10	4-$MeO_2CC_6H_4NO_2$	46.4	2.6 (**2a**)	29.1
5	**3c**	130	10	4-$MeO_2CC_6H_4NO_2$	66.2	11.1 (**2a**)	27.8
6	**3c**	160	6	3,5-$Cl_2C_6H_3NO_2$	77.7	31.0 (**2b**)	13.5
7	**3b**	160	6	3,5-$Cl_2C_6H_3NO_2$	99.4	44.5 (**2b**)	22.3
8	**3a**	160	6	3,5-$Cl_2C_6H_3NO_2$	84.4	18.3 (**2b**)	17.7
9	**3c**	130	10	3,5-$Cl_2C_6H_3NO_2$	81.5	37.3 (**2b**)	32.9
10	**3c**	100	10	3,5-$(CF_3)_2C_6H_3NO_2$	12.6	8.9 (**2c**)	37.4

[a] Experimental conditions: $Ru_3(CO)_{12}$=0.65 mg, 1.0×10^{-3} mmol, mol ratio $Ru_3(CO)_{12}$/**3**/$ArNO_2$=1/3/50, P_{CO}=40 bar, in cyclohexene (1 mL).
[b] Calculated with respect to the starting nitroarene; GC analysis.
[c] Calculated with respect to the converted nitroarene; GC analysis.

The reactions with the oxazolines were run in a similar way to the ones with Ar-BIAN ligands. However, in order to be able to perform the reactions on a smaller scale, an aluminum block having three 12 mm holes was prepared that could be fitted in the autoclave. Three small test tubes were placed in the holes (see Section 4 for details), so that three reactions could be run at the same time, each on a 1 mL scale.

The results of reactions run with the bis-oxazoline ligands are reported in Table 2.

The desired products were obtained, but reaction rates and selectivities are in general lower than those achievable with the use of Ph-BIAN. The two enantiomers of **2a** could be separated by chiral HPLC, employing conditions similar to the ones reported for the analogous ethyl ester,[16] but the enantiomers of **2b**–**d** could not be separated by the same technique, nor by chiral phase gas chromatography. Unfortunately the reactions corresponding to entries 1–5 in Table 2 all gave a completely racemic product. At 100 °C, **1a** did not react to any detectable extent and even the more reactive **1c** only gave a low conversion and a very low selectivity in allylic amine. Thus bis-oxazolines are not suitable ligands for an enantioselective modification of our amination reaction. Other chiral ligands have to be developed that also have to impart a reactivity to the catalytic system at least comparable to the one achievable with Ar-BIAN ligands, so that the reaction can be performed at lower temperatures.

3. Conclusions

In this paper, we have expanded the range of successfully converted substrates for the amination of cyclohexene by nitroarenes and CO, including several nitroarenes having strongly electron-withdrawing substituents. A selective reaction of only one nitro group in 1,4-dinitrobenzene was observed. More importantly, a two step-one pot protocol to an amino substituted derivative has been devised, which allows the reaction to be extended to previously inaccessible products, without problems deriving from polysubstitution. Chiral bis-oxazolines were found to be suitable ligands for the catalytic system, but results are inferior to the ones obtainable with Ar-BIAN ligands and the product formed was found to be racemic. We have also determined that carboxylation of cyclohexene is possible using a ruthenium complex as catalyst and this will be studied in further depth.

4. Experimental

4.1. General procedure

Cyclohexene, THF and hexane were purified by distillation over sodium and stored under dinitrogen before use. $Ru_3(CO)_{12}$[17] was synthesized as reported in the literature. Ph-BIAN was prepared as previously reported,[18–20] but employing our protocol based on the use of oxalate to remove the initially present $ZnCl_2$.[21] All other compounds, except for those mentioned below, were commercial products and were used as received. Gas chromatographic analyses were performed on a Perkin Elmer 8420 capillary gas chromatograph equipped with a PS 255 column. Ri values (Ri=response factor, relative to naphthalene as an internal standard) were determined by the use of solutions of known concentrations of the compounds. GC-MS analyses were performed on a Shimadzu GCMS-QP5050A instrument, equipped with an Equity 5 column. NMR spectra were recorded on a Bruker AC 300 FT, operating at 300 MHz for ^{1}H, at 282 MHz for ^{19}F, and at 75 MHz for ^{13}C. Elemental analyses and mass spectra were recorded in the analytical laboratories of Milan University.

4.1.1. Synthesis of 3c. The synthesis was performed in oven-dried glassware working under a dinitrogen atmosphere and employing standard Schlenk and cannula techniques. After the quenching with water, the remaining operations have been conducted in the air. To a Schlenk tube were added (*R*)-indabox ([3a*R*-[2(3′a*R* *,8′a*S* *),3′aβ,8′aβ]]-(+)-2,2′-methylenebis[3a,8a-dihydro-8*H*-indeno[1,2-*d*]-oxazole, 100.0 mg, 0.303 mmol), tetramethylethylendiamine (TMEDA, 92 μL, 0.61 mmol) and THF (12 mL). After the solid was dissolved, the solution was cooled to −78 °C by an acetone–dry ice bath and LiN–iPr$_2$ (0.8 mmol, 0.40 mL of a 2 M solution in THF/heptane/ethylbenzene) was added. The orange suspension was left to stir at −78 °C for 30 min, then at −20 °C for 2.5 h. At this point, the solution was cooled back to −78 °C and MeI (47 μL, 0.75 mmol) was added. The solution was stirred at this temperature for 30 min, then at −20 °C for the same time and finally at room temperature overnight. A saturated

solution of $NaHCO_3$ (7 mL) was added and, after stirring for 10 min, 2 more mL water were added to dissolve a white solid suspended in the aqueous phase. The two phases were separated, the aqueous phase was extracted with THF (3×10 mL) and the combined extracts were joined to the organic phase. After drying with sodium sulfate, the organic solution was evaporated to dryness in vacuo and the resulting solid, consisting of white and orange crystals, was recrystallized from hexane (50 mL) to afford **3c** as colorless needle-like crystals (61.1 mg, 56.2% yield). Anal. Calcd for $C_{23}H_{22}N_2O_2$: C, 77.07; H, 6.19; N, 7.82. Found: C, 76.80; H, 6.09; N, 8.11. ^{1}H NMR (300 MHz, $CDCl_3$, 25 °C, TMS): δ=1.44 (s, 6H, CH_3), 2.97 (d, J_{gem}=17.9 Hz, 2H, −CHC(H)*H*C), 3.29 (dd, J_{gem}=17.9, J_{12}=7.1 Hz, 2H, −CHC(*H*)HC), 5.29 (pt, 2H, CH−O), 5.54 (d, J_{12}=7.9 Hz, 2H, CH−N), 7.29 (m, 6H, Ar−H), 7.51 (m, 2H, Ar−H). MS (70 eV, EI): *m*/*z*: 358 [M^+].

4.2. Catalytic reactions

In a typical reaction, the nitroarene, $Ru_3(CO)_{12}$ and the ligand (see Tables 1 and 2) were weighed in a glass liner. The liner was placed inside a Schlenk tube with a wide mouth under dinitrogen and was frozen at −78 °C with dry ice, evacuated and filled with dinitrogen, after which the solvent was added. After the solvent was also frozen, the liner was closed with a screw cap having a glass wool-filled open mouth which allows for gaseous reagents exchange and rapidly transferred to a 200 mL stainless steel autoclave with magnetic stirring. The autoclave was then evacuated and filled with dinitrogen three times. CO was then charged at room temperature at the required pressure and the autoclave was immersed in an oil bath preheated at the required temperature. Other experimental conditions are reported in Tables 1 and 2. At the end of the reaction the autoclave was cooled with an ice bath, vented and the products were analyzed by gas chromatography (naphthalene as an internal standard) and then extracted with acids as detailed in the following for each compound. In the case of the synthesis of **2e**, after the amination reaction employing **1d** as substrate was over (conditions as in entry 1 of Table 1), the autoclave was vented, the glass liner moved to the same Schlenk tube employed during the initial preparation and previously placed under a dinitrogen atmosphere and opened in a dinitrogen flux. Water (0.3 mL) and methanol (1.5 mL) were added. The same procedure described before was then employed and the second step was run at 180 °C under 30 bar CO for 4 h. Handling of the reaction solution in the air should be avoided as much as possible, since the catalytically active species Ru(Ph-BIAN)$(CO)_3$ (intense purple color), formed during the reaction, is very air sensitive. The reactions with bis-oxazolines as ligands were performed in a similar way, but on a smaller scale. In this case, three 10 mm wide ×40 mm high test tubes were employed instead of the glass liner, each having a miniature glass wool-filled screw cap similar to the one of the larger liner. The three test tubes were located in the holes of an aluminum block designed to fit the autoclave. Other operations were analogous to the ones described above except that stock solutions of $Ru_3(CO)_{12}$, the ligand and the nitroarene were prepared and the reagent amounts measured by volume to avoid the errors in weighing very small amounts of materials.

4.3. Separation and purification of the allylamines 2

Compounds **2a**, **2b**. The solution after the withdrawal for the GC analysis was extracted with 1 M aqueous HCl (3×5 mL) to remove the byproduct anilines The organic phase was then extracted with ~3 M H_2O/MeOH HCl solution, obtained by mixing 1 volume 37% HCl with 1 volume H_2O and 2 volumes MeOH (3×5 mL). The combined aqueous phases of the second extraction were made basic by the addition of NaOH and back extracted with CH_2Cl_2 (3×5 mL). After drying the organic phase with sodium sulfate, it was evaporated to dryness in vacuo and loaded on a short (7 cm) silica pad. The mixture is eluted with CH_2Cl_2 keeping all the eluate together, until a brown band does not approach the end of the pad, at which point the elution is stopped. The eluate is evaporated to dryness to afford the pure product.

Compounds **2c**, **2d**. The same procedure was employed as above, but a ~6 M H_2O/MeOH HCl solution (obtained by mixing equal volumes of 37% HCl and methanol) was necessary to efficiently extract these allylic amines.

Compound **2e**. A clean separation of **2e** from 1,4-diaminobenzene and aniline could not be achieved by simple acidic extraction. The amines were thus extracted together with 3 M H_2O/MeOH HCl. During the chromatographic separation, a yellow impurity band was first eluted with CH_2Cl_2, after which $CHCl_3$ was added and the red colored **2e** collected. The thus obtained product still contains small amounts of diaminobenzene and aniline. However, heating at 60 °C in vacuo the red oil for 3 h, these more volatile impurity evaporated and the product was shown by GC to contain about 1% of 1,4-diaminobenzene as the only contaminant.

4.4. Identification of the organic products of catalysis

The by-products anilines are all commercial products and were identified by comparison of their CG and CG-MS spectra with those of authentic samples. Compound **2a** is a colorless solid, **2b** and **2c** are colorless oils, **2d** is a yellow solid, and **2e** is a red oil. Compound **2d**[22] has been previously reported in the literature. The ^{1}H NMR spectrum of our sample was consistent with the one reported in the literature. The ^{13}C NMR and mass spectra of **2d** are anyway reported in the following because this data has not been reported previously. After the chromatographic separation, no impurity could be detected in the GC and ^{1}H NMR spectra of the allylamines (except for **2e**, as mentioned above). Thus, the purified compounds are evaluated to be at least 98% pure.

4.4.1. Compound 2a. ^{1}H NMR ($CDCl_3$, 25 °C, TMS): δ=1.65–1.98 (m, 6H, −C*H*$_2$−C*H*$_2$−C*H*$_2$−), 3.87 (s, 3H, $COOCH_3$), 4.08 (s br, 2H, −C*H*−N*H*, 1H exc D_2O), 5.74 (m, 1H, −CH_2−C*H*═CH−CH−), 5.91 (m, 1H, −CH_2−CH═C*H*−CH−), 6.57 (d, J_{ortho}=8.6 Hz, 2H, Ar−H), 7.87 (d, J_{ortho}=8.6 Hz, 2H, Ar−H). ^{13}C NMR ($CDCl_3$, 25 °C, TMS): δ=19.59, 25.12, 28.79, 47.58, 51.58, 111.84, 118.17, 127.64, 131.02, 131.71, 151.01, 167.37. MS (70 eV, EI): *m*/*z*: 231 [M^+]. Anal. Calcd for $C_{14}H_{17}NO_2$: C, 72.70; H, 7.41; N, 6.06. Found: C, 72.42; H, 7.50; N, 5.75.

4.4.2. Compound 2b. ^{1}H NMR ($CDCl_3$, 25 °C, TMS): δ=1.60–1.95 (m, 6H, –C*H*$_2$–C*H*$_2$–C*H*$_2$–), 3.82 (s br, 1H, NH, exc D_2O), 3.93 (s br, 1H, –C*H*–NH), 5.70 (m, 1H, –CH$_2$–C*H*=CH–CH–), 5.90 (m, 1H, –CH$_2$–CH=C*H*–CH–), 6.47 (s 2H, Ar–H), 6.65 (s, 1H, Ar–H). ^{13}C NMR ($CDCl_3$, 25 °C, TMS): δ=19.54, 25.10, 28.69, 47.86, 51.58, 111.22, 116.76, 127.48, 131.12, 135.58, 148.87. MS (70 eV, EI): *m*/*z*: 241 [M$^+$]. Anal. Calcd for $C_{12}H_{13}NCl_2$: C, 59.52; H, 5.41; N, 5.78. Found: C, 59.30; H, 5.57; N, 6.12.

4.4.3. Compound 2c. ^{1}H NMR ($CDCl_3$, 25 °C, TMS): δ=1.56–1.96 (m, 6H, –C*H*$_2$–C*H*$_2$–C*H*$_2$–), 4.08 (s br, 2H, –C*H*–N*H*, 1H exc D_2O), 5.72 (m, 1H, –CH$_2$–C*H*=CH–CH–), 5.96 (m, 1H, –CH$_2$–CH=C*H*–CH–), 6.94 (s, 2H, Ar–H), 7.13 (s, 1H, Ar–H). ^{13}C NMR ($CDCl_3$, 25 °C, TMS): δ=19.79, 25.36, 28.83, 48.15, 110.21, 112.45, 123.98 (q, J_{C-F}=272.5 Hz), 127.36, 131.81, 132.88 (q, J_{C-F}=32.8 Hz), 148.15. ^{19}F NMR ($CDCl_3$, 25 °C, TMS): δ=−63.53. MS (70 eV, EI): *m*/*z*: 309 [M$^+$]. Anal. Calcd for $C_{14}H_{13}NF_6$: C, 54.37; H, 4.24; N, 4.53. Found: C, 54.00; H, 4.52; N, 4.80.

4.4.4. Compound 2d. ^{1}H NMR ($CDCl_3$, 25 °C, TMS): δ=1.62–2.02 (m, 6H, –C*H*$_2$–C*H*$_2$–C*H*$_2$–), 4.11 (s br, 1H, NH, exc D_2O), 4.49 (s br, 1H, –C*H*–NH), 5.73 (m, 1H, –CH$_2$–C*H*=CH–CH–), 5.97 (m, 1H, –CH$_2$–CH=C*H*–CH–), 6.55 (d, J_{ortho}=9.2 Hz, 2H, Ar–H), 8.10 (d, J_{ortho}=9.2 Hz, 2H, Ar–H). ^{13}C NMR ($CDCl_3$, 25 °C, TMS): δ=19.36, 24.92, 28.56, 47.78, 111.34, 126.53, 126.65, 131.79, 137.89, 152.29. MS (70 eV, EI): *m*/*z*: 218 [M$^+$]. Anal. Calcd for $C_{12}H_{14}N_2O_2$: C, 66.04; H, 6.47; N, 12.84. Found: C, 65.77; H, 6.13; N, 13.16.

4.4.5. Compound 2e. ^{1}H NMR ($CDCl_3$, 25 °C, TMS): δ=1.58–1.92 (m, 6H, –C*H*$_2$–C*H*$_2$–C*H*$_2$–), 3.27 (s br, 3H, NH and NH_2, exc D_2O), 3.90 (s br, 1H, –C*H*–NH), 5.80 (m, 2H, –CH$_2$–C*H*=C*H*–CH–), 6.58 (m, 4H, Ar–H). ^{13}C NMR ($CDCl_3$, 25 °C, TMS): δ=20.24, 25.65, 29.56, 49.68, 115.89, 117.37, 129.55, 130.04, 138.20, 140.87. MS (70 eV, EI): *m*/*z*: 188 [M$^+$]. Anal. Calcd for $C_{12}H_{16}N_2$: C, 76.56; H, 8.57; N, 14.88. Found: C, 76.20; H, 8.22; N, 14.60.

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References and notes

1. Johannsen, M.; Jørgensen, K. A. *Chem. Rev.* **1998**, *98*, 1689–1708, and references therein.
2. Cenini, S.; Ragaini, F.; Tollari, S.; Paone, D. *J. Am. Chem. Soc.* **1996**, *118*, 11964–11965.
3. Ragaini, F.; Cenini, S.; Tollari, S.; Tummolillo, G.; Beltrami, R. *Organometallics* **1999**, *18*, 928–942.
4. Ragaini, F.; Cenini, S.; Borsani, E.; Dompé, M.; Gallo, E. *Organometallics* **2001**, *20*, 3390–3398.
5. Cenini, S.; Ragaini, F. *Catalytic Reductive Carbonylation of Organic Nitro Compounds*; Kluwer: Dordrecht, 1997; Chapter 6 and references therein.
6. Boger, D. L.; Weinreb, S. N. *Hetero Diels–Alder Methodology in Organic Synthesis*; Academic: New York, 1987; and references therein.
7. Srivastava, R. S.; Nicholas, K. M. *Chem. Commun.* **1998**, 2705–2706.
8. Ragaini, F.; Cenini, S.; Tollari, S. *J. Mol. Catal.* **1993**, *85*, L1–L5.
9. Ragaini, F.; Cenini, S.; Gasperini, M. *J. Mol. Catal. (A)* **2001**, *174*, 51–57.
10. Drent, E. Eur. Pat. Appl. EP 310168 A2, 1989. *Chem. Abstr. 119*, 59984.
11. Larkin, J.M. U.S. US 4588834 A, 1986. *Chem. Abstr. 105*, 42340.
12. Ragaini, F.; Pizzotti, M.; Cenini, S.; Abbotto, A.; Pagani, G. A.; Demartin, F. *J. Organomet. Chem.* **1995**, *489*, 107–112.
13. Davies, I. W.; Senanayake, C. H.; Larsen, R. D.; Verhoeven, T. R.; Reider, P. J. *Tetrahedron Lett.* **1996**, *37*, 813–814.
14. Denmark, S. E.; Stiff, C. M. *J. Org. Chem.* **2000**, *65*, 5875–5878.
15. Davies, I. W.; Gerena, L.; Castonguay, L.; Senanayake, C. H.; Larsen, R. D.; Verhoeven, T. R.; Reider, P. J. *Chem. Commun.* **1996**, 1753–1754.
16. Löber, O.; Kawatsura, M.; Hartwig, J. F. *J. Am. Chem. Soc.* **2001**, *123*, 436–437.
17. Eady, C. R.; Jackson, P. F.; Johnson, B. F. G.; Lewis, J.; Malatesta, M. C.; McPartlin, M.; Nelson, W. J. *J. Chem. Soc. Dalton Trans.* **1980**, 383–392.
18. Dvolaitzky, M. *C. R. Acad. Sci. Paris, Ser. C* **1969**, *268*, 1811–1813, *Chem. Abstr.* **1969**, *71*, 61566b.
19. Matei, I.; Lixandru, T. *Bul. Ist. Politeh. Iasi* **1967**, *13*, 245–255, *Chem. Abstr.* **1969**, *70*, 3623m.
20. van Asselt, R.; Elsevier, C. J.; Smeets, W. J. J.; Spek, A. L.; Benedix, R. *Recl Trav. Pays Bas* **1994**, *113*, 88–98.
21. Gasperini, M.; Ragaini, F.; Cenini, S. *Organometallics* **2002**, *21*, 2950–2957.
22. Moreno-Mañas, M.; Morral, L.; Pleixats, R. *J. Org. Chem.* **1998**, *63*, 6160–6166.