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COMMUNICATION

Efficient and highly selective iron-catalyzed reduction of nitroarenes†

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Pyrolysis of iron–phenanthroline complexes supported on carbon leads to highly selective catalysts for the reduction of structurally diverse nitroarenes to anilines in 90–99% yields. Excellent chemoselectivity for the nitro group reduction is demonstrated.

Aromatic amines are central intermediates and key precursors in the synthesis of dyes, pigments, agrochemicals, polymers, herbicides, and pharmaceuticals.[1] Regarding their synthesis the selective reduction of functionalized nitro compounds represents the most important and versatile methodology. Apart from catalytic hydrogenations,[2,3] various stoichiometric reducing agents[4–9] have also been successfully used to reduce nitro compounds in the presence of metal catalysts based on Rh,[7] Pd,[4,5,7] and Ru.[8,9] Despite all these achievements the development of novel protocols with high chemoselectivity towards other reducible moieties is still desired.[10]

Traditionally, nitro group reductions are carried out using precious metal catalysts.[4,5,7–10] However, these precious metal complexes are expensive and usually air- and moisture-sensitive. The limited availability of these metals makes it desirable to search for more economical and environmentally friendly alternatives. A possible solution of this problem could be the increased utilization of catalysts based on bio-relevant metals, such as iron, copper, and cobalt.[11–18] Especially, iron offers significant advantages compared to precious metals,[13] since it is the second most abundant metal in the earth crust (4.7%). Moreover, iron compounds are relatively non-toxic, and inexpensive.

Nevertheless, there are only few reports available on iron-catalyzed reduction of nitroarenes with various reducing agents.[14–18] To overcome the problem of catalyst separation, also heterogeneous catalysts have been used for this transformation.[10,19]

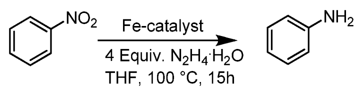
Based on our background in homogeneous iron catalysis,[20] recently we started a program to synthesize and apply novel carbon-supported iron catalyst systems for selective redox processes. Simple carbon-supported iron catalysts are known to be less active in reduction reactions. On the other hand, carbon-supported iron–nitrogen systems have been shown to be interesting oxygen reduction catalysts.[21] Hence, we got attracted by these materials. Here, for the first time we are showing that such heterogeneous iron–nitrogen materials represent excellent catalysts for the selective reduction of aromatic nitro compounds to the corresponding amines.

An initial screening on the activity of a pyrolyzed carbon-supported iron–phenanthroline complex for the transfer hydrogenation[22] of nitrobenzene revealed excellent activity in the presence of hydrazine hydrate as a reducing agent. Hydrazine hydrate is widely used in organic synthesis,[11,17,18,23] because it produces only nitrogen and water as by-products.

For the preparation of the heterogeneous catalyst Fe–phenanthroline/C,[21a] we mixed $Fe(OAc)_2$ with 1,10-phenanthroline (Fe : phenanthroline = 1 : 2) and commercially available vulcan XC72R carbon powder and pyrolyzed this mixture at 800 °C for 2 h.

First catalytic experiments were carried out with nitrobenzene as a model substrate. Obviously, there is no appreciable reaction in the absence of catalyst (Table 1, entry 1). Notably, using homogeneous $Fe(OAc)_2$ with or without added phenanthroline only little conversion is seen (<10%; Table 1, entries 2 and 3). Similarly, carbon-supported catalysts based on $Fe(OAc)_2$ alone, and with phenanthroline under non-pyrolyzed conditions are not active for the reduction (Table 1, entries 4 and 5). However, using pyrolyzed carbon-supported $Fe(OAc)_2$ the reaction took place with 30% conversion and 20% yield (Table 2, entry 6). Conversion and yield could not be improved

Table 1 Reduction of nitrobenzene with different Fe-catalysts[a,b]



Entry	Carbon support	Iron salt	L	Pyrolysis (°C, h, gas)	C (%)	Y (%)
1[a]	—	—	—	—	2	1
2[a]	—	$Fe(OAc)_2$	—	—	5	2
3[a]	—	$Fe(OAc)_2$	L	—	10	3
4[b]	Vulcan XC72R	$Fe(OAc)_2$	—	—	8	5
5[b]	Vulcan XC72R	$Fe(OAc)_2$	L	—	10	5
6[b]	Vulcan XC72R	$Fe(OAc)_2$	—	800, 2, Ar	30	20
7[b]	Vulcan XC72R	$Fe(OAc)_2$	L	800, 2, Ar	**100**	**99**
8[b]	Vulcan XC72R	—	—	—	5	3

L = 1,10-phenanthroline; C = conv.; Y = yield. [a] Homogeneous conditions: 0.5 mmol nitrobenzene, 2 mmol hydrazine hydrate, 0.025 mmol $Fe(OAc)_2$, 0.05 mmol L. [b] Heterogeneous conditions: 0.5 mmol $PhNO_2$, 2 mmol hydrazine hydrate, 1 mol% Fe.

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† Electronic supplementary information (ESI) available: Experimental procedure and TEM images. See DOI: 10.1039/c1cc13728j

Table 2 Reduction of nitroarenes with Fe–phenanthroline/C[a]

$$\text{R–NO}_2 \xrightarrow[\text{4 Equiv. N}_2\text{H}_4{\cdot}\text{H}_2\text{O, THF, 100 °C, 10h}]{\text{Fe-phenanthroline /C (1 mol\% Fe)}} \text{R–NH}_2$$

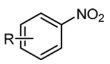
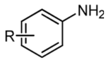
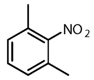
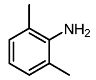
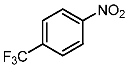
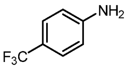
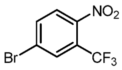
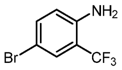
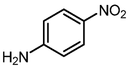
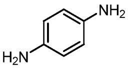
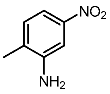
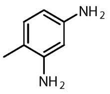
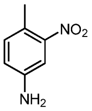
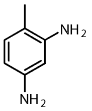
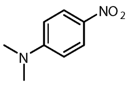
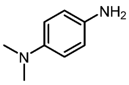
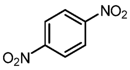
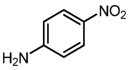
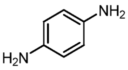
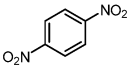
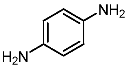
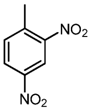
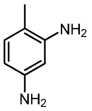
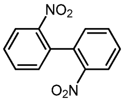
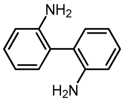
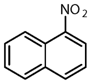
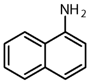
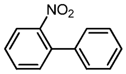
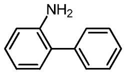
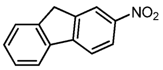
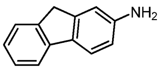
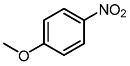
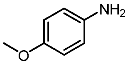
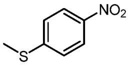
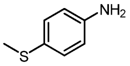
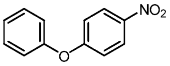
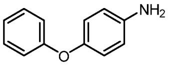
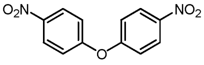
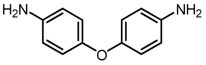
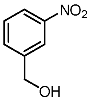
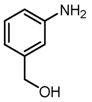
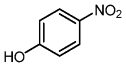
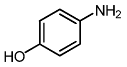
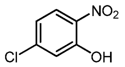
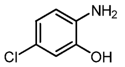
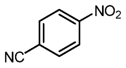
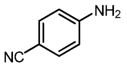
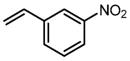
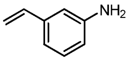
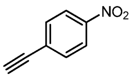
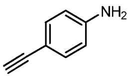
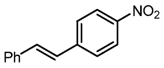
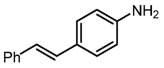
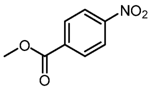
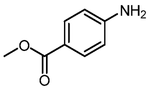
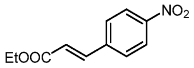
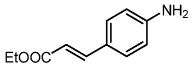
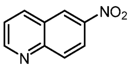
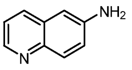
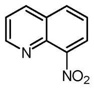
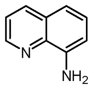
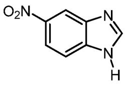
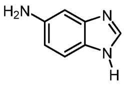
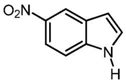
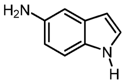
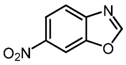
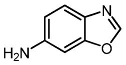
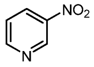
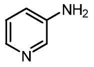
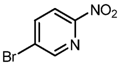
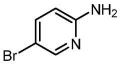
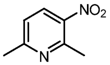
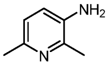
Entry	Nitro compound	Aniline	Yield (%)	Selectivity (%)
1		 R = H	99	99
2		R = 4-Br	99	99
3		R = 4-Cl	99 96	99 96[c]
4		R = 4-I	99	99
5		R = 4-F	90	90
6		R = 2-Cl	99	99
7		R = 3-Cl	99	99
8		R = 3,5-dichloro	99	99
9		R = 3,4,5-trichloro	99	99
10		R = 4-Me	99	99
11		R = 4–ethyl	99	99
12		R = 4-iPr	99	99
13		R = 4-ter-butyl	99	99
14			93	99
15			99	99
16			99	99
17			99	99
18			95	96
19			94	95
20			95	95
21			90	90
			9	9
22[b]			98	98
23[b]			94	95
24[b]			98	98
25			99	99
26			99	99
27			99	99
28			99	99
29			95 95	96 95[c]
30			99	99
31[b]			98	98
32			95	95
33			97	97
34			93	94
35			99	99
36			96	96
37			96	96
38			99	99
39			99	99
40			99	99
41			99	99
42			98	98
43			99 99	99 99
44			95	95[c]
45			96	96
46			96	97

Table 2 (*continued*)

Entry	Nitro compound	Aniline	Yield (%)	Selectivity (%)
47			92	93
48			90	98

[a] Reaction conditions: 0.5 mmol nitro compound, 2 mmol hydrazine hydrate, Fe–phenanthroline/C (1 mol% Fe), 100 °C, 10 h. [b] Reaction conditions: 0.5 mmol nitro compound, 4 mmol hydrazine hydrate, Fe–phenanthroline/C (1 mol% Fe), 100 °C. [c] Scaled up by factor 10 and isolated yields are given.

with this catalyst even after 24 h reaction time. To our delight, pyrolysis of the *in situ*-generated $Fe(OAc)_2$–phenanthroline complex supported on carbon led to a highly active system. Here, nitrobenzene is completely reduced to aniline in 99% yield (Table 1, entry 7). Notably, the pyrolyzed catalyst system is highly stable and can be re-used.

As shown in Table 2, a variety of nitro compounds can be highly selectively reduced under the optimized conditions in the presence of Fe–phenanthroline/C. Except for the fluorine-substituted substrate (90%), excellent yields (99%) of the corresponding haloanilines are achieved (Table 2, entries 2–9). Obviously, in none of these cases significant amounts of dehalogenations occurred. The protocol also works well for the reduction of other substituted nitroarenes (Table 2, entries 10–16). Even, sterically hindered 2,6-dimethylnitrobenzene selectively gave 93% aniline (Table 2, entry 14). The more active 4-nitrobenzotrifluoride and 5-bromo-2-nitrobenzotrifluoride are also completely reduced to the corresponding anilines in excellent yield (99%, Table 2, entries 15 and 16). Notably, nitro anilines are selectively reduced to dianilines in >93% yield (Table 2, entries 17–20). Reduction of 1,4-dinitrobenzene proceeded selectively, affording 90% 4-nitroaniline (Table 2, entry 21). In contrast, complete reduction of both the nitro groups of dinitrobenzenes was achieved using 4 additional equivalents of hydrazine hydrate to produce diaminobenzenes in 94–98% yield (Table 2, entries 22–24). This makes it likely that the first step in the reduction of the nitro group is the rate determining step in the overall reduction sequence.

Next, we turned our interest towards the chemoselective reduction of nitroarenes in the presence of other reducible groups. Notably, functional groups such as cyano, ether, thioether and ester groups, and as well as more challenging C–C double and triple bonds are not affected under these conditions (Table 2, entries 28–40). In all these cases the nitro group was chemoselectively reduced to anilines in 93–99% yield. More specifically, the reduction of cyano-substituted nitrobenzene, which is an important transformation in organic chemistry, gave 99% of 4-cyanoaniline (Table 2, entry 35). Interestingly, the catalyst also allows for the selective synthesis of amino heterocycles in 92–99% yields from the corresponding heterocycles (Table 2, entries 41–48).

Finally, the recycling and reusability of catalyst was tested in the reduction of the model system. Indeed, Fe–phenanthroline/C is successfully recycled and reused 6 times without any significant loss of catalytic activity (see the ESI†).

In conclusion, an inexpensive and recyclable iron catalyst system is introduced for the efficient reduction of nitro compounds using hydrazine hydrate. Our convenient and easy to perform procedure is applicable with a series of structurally diverse nitroarenes. Notably, the nitro group is chemoselectively reduced in the presence of other sensitive groups such as C=C, C≡C, C≡N, OH, ether, thioether and ester groups.

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