Available online at www.sciencedirect.com
ScienceDirect
Tetrahedron 64 (2008) 1847–1852
Tetrahedron
www.elsevier.com/locate/tet

Hydrogen-transfer reduction of carbonyl compounds promoted by nickel nanoparticles

Francisco Alonso*, Paola Riente, Miguel Yus*

Departamento de Química Orgánica, Facultad de Ciencias, and Instituto de Síntesis Orgánica (ISO), Universidad de Alicante, Apdo. 99, E-03080 Alicante, Spain

Received 4 October 2007; received in revised form 26 November 2007; accepted 28 November 2007
Available online 4 December 2007

This paper is dedicated to Professor Koichiro Oshima on occasion of his 60th birthday

Abstract

Nickel(0) nanoparticles, generated from nickel(II) chloride, lithium powder and a catalytic amount of 4,4-di-*tert*-butylbiphenyl (DTBB) in THF at room temperature, have been found to promote the reduction of a variety of ketones and aldehydes by transfer hydrogenation using isopropanol as the hydrogen donor. The nickel nanoparticles were characterised and could be re-utilised with a good performance in the absence of a base. A mechanistic study demonstrates that the reaction proceeds through a dihydride-type mechanism.

Keywords: Carbonyl compounds; Nickel nanoparticles; Hydrogen transfer

1. Introduction

A continuous interest has been shown towards the reduction of carbonyl compounds to the corresponding alcohols as a fundamental and common functional-group transformation in synthetic organic chemistry. Among the different methodologies to perform this reaction, four important general procedures can be highlighted involving the use of (a) metal hydrides, (b) dissolving metals, (c) catalytic hydrogenation, and (d) transfer hydrogenation.[1] Other methods, such as electrochemical or enzymatic methods are of less general application. Hydrogen-transfer reactions[2] are advantageous with respect to other reduction methods because of several reasons: (a) the hydrogen donor is easy to handle (no gas containment or pressure vessels are necessary), cheap and environmentally friendly (e.g., isopropanol), (b) possible hazards are minimised, (c) the mild reaction conditions applied can afford enhanced selectivity, (d) catalytic asymmetric transfer hydrogenation can be applied in the presence of chiral ligands.[3]

The transfer hydrogenation of ketones has been mostly accomplished using isopropanol as hydrogen donor under homogeneous conditions in the presence of noble metal complexes. The most efficient catalysts devised so far are centred on second or third row metals in d^6 or d^8 electronic configuration, Ru,[4] Rh[5] and Ir[6] complexes being, apparently, more active than comparable Pd, Pt, and Os derivatives. In fact, ruthenium complexes have been by far the most studied catalysts, especially for the asymmetric transfer hydrogenation of aromatic ketones[7] and from the mechanistic point of view.[8] Less attention has been paid, however, to the hydrogen-transfer reduction of non-aromatic carbonyl compounds, as well as to processes under heterogeneous conditions or involving non-noble metals. In fact, the use of heterogeneous catalysts offers several advantages over the homogeneous systems, such as easy recovery, recycling and enhanced stability.

In this sense, nickel appears as a potential alternative to the above expensive transition-metal complexes but little studied in hydrogen-transfer reactions with isopropanol. For instance, an activated form of nickel, prepared by thermal decomposition of nickel isopropoxide in boiling isopropanol, catalysed the transfer hydrogenation of aliphatic ketones and acetophenone

* Corresponding authors. Fax: +34 965903549.
E-mail addresses: falonso@ua.es (F. Alonso), yus@ua.es (M. Yus).

0040-4020/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.tet.2007.11.093

in isopropanol at 95–100 °C.[9] The $NiBr_2$–NaOH–*i*-PrOH system also showed to be effective in the reduction of a variety of ketones, but longer reaction times were needed in order to achieve higher conversions.[10] A macrocyclic nickel(II) complex,[11] Ni-stabilised zirconia,[12] and mesoporous NiMCM molecular sieves[13] were primarily applied to the reduction of aromatic substrates, albeit the latter two could be re-used several times without affecting their activity. In all these cases, the addition of an external base was mandatory for the reaction to take place. More recently, an excess of Raney nickel in refluxing isopropanol containing a trace of HCl reduced a series of aliphatic aldehydes to the corresponding primary alcohols.[14]

On the other hand, we have recently reported the fast synthesis of nickel(0) nanoparticles from different nickel(II) chloride-containing systems by reduction with lithium powder and a catalytic amount of an arene in THF at room temperature.[15] The high reactivity and versatility of these nanoparticles were demonstrated in the reduction of a wide variety of functional groups,[16] highly selective semihydrogenation of alkynes and dienes,[17] conjugate reduction of α,β-unsaturated carbonyl compounds,[18] and more recently, in the α-alkylation of ketones with primary alcohols,[19] in all the cases under mild reaction conditions. Apparently, a hydrogen-transfer process might be one of the key steps in the latter application (the reaction mechanism is now under study), and was demonstrated to be present, at least in part, in other applications involving an alcohol. Therefore, we envisaged the possibility of applying these nickel nanoparticles to the transfer hydrogenation of carbonyl compounds.

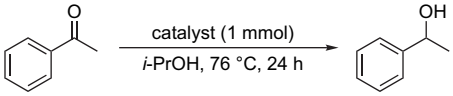
We want to present herein the transfer hydrogenation of a representative series of aromatic and aliphatic carbonyl compounds, promoted by nickel(0) nanoparticles in isopropanol in the absence of any added base.

2. Results and discussion

The nickel(0) nanoparticles (NiNPs) were generated from anhydrous nickel(II) chloride, lithium powder and a catalytic amount of DTBB (4,4′-di-*tert*-butylbiphenyl, 5 mol %) in THF at room temperature. A preliminary study was carried out using acetophenone as a model substrate in the presence of different catalysts (Table 1). It is noteworthy that, under the conditions shown in Table 1, only the NiNPs were able to reduce acetophenone to 1-phenylethanol, whereas Raney Ni led to the hydrogenolysis product, ethylbenzene.[20] Two blank experiments, in the absence of isopropanol (only THF as solvent) and in the absence of nickel gave the unreacted starting material. Low yield of the expected product was obtained at room temperature or by using 10 and 20 mol % NiNPs.

With this methodology in hand, we first studied the transfer hydrogenation of aromatic carbonyl compounds (Table 2). A series of differently substituted acetophenones were reduced, in a fast manner, to the corresponding alcohols in modest-to-good isolated yields (entries 1–6), the position and electronic character of the substituent notably affecting the yield. For instance, 4-trifluoromethylacetophenone was reduced in 57% yield (entry 2), but 3-trifluoromethylacetophenone was reduced in only 27% isolated yield and 2-trifluoromethylacetophenone was unaffected. As expected, the opposite effect was observed for methoxy-substituted acetophenones, the 3-substituted giving much better yield in shorter reaction time than the 4-substituted acetophenone (entries 3 and 4). Less difference in yield was observed for methyl substituted acetophenones (entries 5 and 6), whereas butyrophenone was reduced in

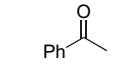
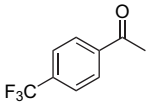
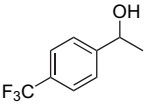
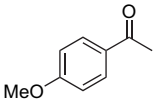
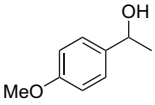
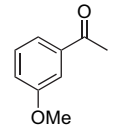
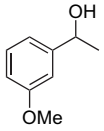
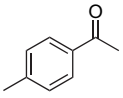
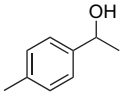
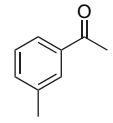
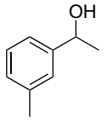
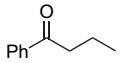
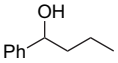
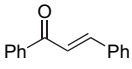
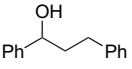
Table 1
Transfer hydrogenation of acetophenone with different nickel catalysts



Entry	Catalyst	Product	Yield[a] (%)
1	NiNPs	1-Phenylethanol	94
2	Raney Ni	Ethylbenzene	95
3	Ni–Al	Acetophenone	100
4	Ni/TiO_2	Acetophenone	100
5	Ni/SiO_2–Al_2O_3	Acetophenone	100
6	NiO	Acetophenone	100

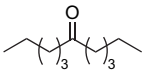
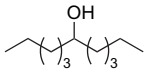
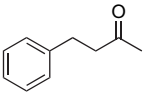
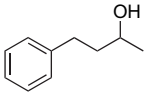
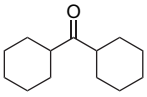
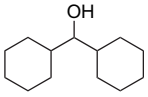
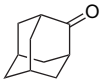
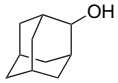
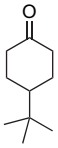
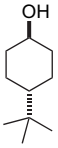
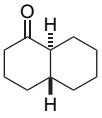
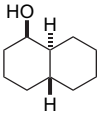
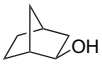
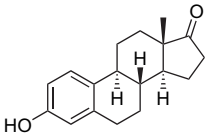
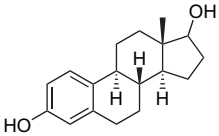
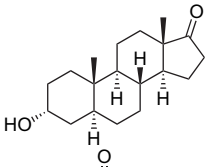
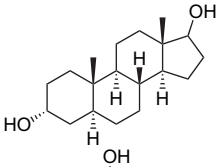
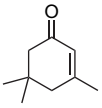
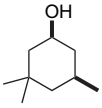
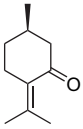
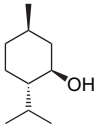
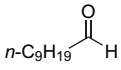
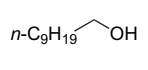
[a] GLC yield.

Table 2
Aromatic carbonyl compounds reduced by hydrogen-transfer with NiNPs-*i*-PrOH[a]

Entry	Substrate	*t* (h)	Product	Yield[b] (%)
1		1		82
2		1		57
3		24		34
4		1		73
5		1		72
6		1		51
7		1		73
8		1		86
9		2		42

[a] Substrate (1 mmol), NiNPs (1 mmol) in THF (2 mL), *i*-PrOH (4 mL), 76 °C.
[b] Isolated yield after column chromatography (hexane/EtOAc).

Table 3
Aliphatic carbonyl compounds reduced by hydrogen-transfer with NiNPs-*i*-PrOH[a]

Entry	Substrate	*t* (h)	Product	Yield[b] (%)
1		1		73
2		1		83
3		48		53
4		1		92
5		1		72[c]
6		1		64[d]
7		1		58[e]
8		1		84[f]
9		1		89[f]
10		2		70
11		1		39[g]
12		1		62[h]
13		1		40[i]

[a] Substrate (1 mmol), NiNPs (1 mmol) in THF (2 mL), *i*-PrOH (4 mL), 76 °C.
[b] Isolated yield after column chromatography (hexane/EtOAc).
[c] Isolated yield of the trans stereoisomer. Diastereomeric ratio: trans/cis 85:15. The cis stereoisomer was isolated in 13% yield.
[d] Diastereomeric ratio: cis/trans 90:10.
[e] Diastereomeric ratio: *exo*/*endo* 85:15.
[f] Diastereomeric ratio: 1:1.
[g] Diastereomeric ratio: cis/trans 92:8.
[h] Diastereomeric ratio: (−)-menthol/neoisomenthol/neomenthol 77:9:14.
[i] GLC yield.

good yield (entry 7). Surprisingly, chloro- and bromo-substituted acetophenones remained untouched under the above conditions. The reduction of chalcone gave the corresponding saturated alcohol in high yield (entry 8). Benzaldehyde was reduced to benzyl alcohol in modest yield (entry 9) due to partial hydrogenolysis leading to toluene.

We studied next the transfer hydrogenation of aliphatic ketones (Table 3). Dialkyl ketones such as 6-undecanone and 4-phenyl-2-butanone gave the corresponding alcohols in good yields and short reaction times (entries 1 and 2). However, the more sterically demanding dicyclohexyl ketone required much longer reaction time to give dicyclohexyl methanol in moderate yield (entry 3). A variety of cyclic ketones were also readily reduced, some of them prone to yield diastereomeric alcohol products. 2-Adamantanone furnished 2-adamantanol in excellent isolated yield (entry 4). In the case of 4-*tert*-butylcyclohexanone, the thermodynamically more stable equatorial alcohol, *trans*-4-*tert*-butylcyclohexanol (72% yield), was the major product (eq/ax 85:15) (entry 5). The minor axial alcohol *cis*-4-*tert*-butylcyclohexanol could be isolated by column chromatography in 13% yield. The reduction of *trans*-decalone provided an ax/eq 90:10 ratio of the corresponding epimeric alcohols (entry 6), whereas (±)-norcamphor led mainly to the more stable of the two possible norborneol stereoisomers: *exo*/*endo* 85:15 (entry 7). Interestingly, the steroids oestrone and androsterone were transformed in high yields into oestradiol and androstanediol, respectively, in both cases as a 1:1 mixture of diastereoisomers (entries 8 and 9).

The reduction of α,β-unsaturated ketones furnished the corresponding saturated alcohols in modest to good yields (entries 10–12). Regarding the stereochemistry of the reaction products, isophorone was reduced to the more stable 1,5-diequatorial 3,3,5-trimethylcyclohexanol with high diastereoselectivity. The reduction of (+)-pulegone also rendered the most stable of the four possible stereoisomers, (−)-menthol, as the major product, accompanied by minor amounts of neomenthol and neoisomenthol (entry 12, footnote h). The aliphatic aldehyde *n*-decanal was reduced to *n*-decanol in modest yield due to the competitive condensation reaction (entry 13).

The formation of nickel nanoparticles was confirmed by carrying out a blank experiment consisting of a standard reaction in the absence of the substrate (i.e., with nickel(II) chloride, lithium, DTBB, THF, and isopropanol at 76 °C). Droplets of the solution containing the nickel nanoparticles at different reaction times (1, 4, and 7 h) were analysed by transmission electron microscopy (TEM), showing similar results. A typical TEM micrograph and size distribution graphic are depicted in Figures 1 and 2, respectively. Spherical, monodisperse, and highly uniform nanoparticles were obtained according with the narrow range of particle size observed (0.75–2.88 nm, ca. 1.75±1.00 nm). Interestingly, most of the nickel nanoparticles had diameters <2 nm (ca. 75%). This result is quite different from that obtained when the nanoparticles were prepared at room temperature in only THF (25% of the nanoparticles <2 nm) but similar to that in the presence of ethanol at room temperature.[15] Therefore, it can

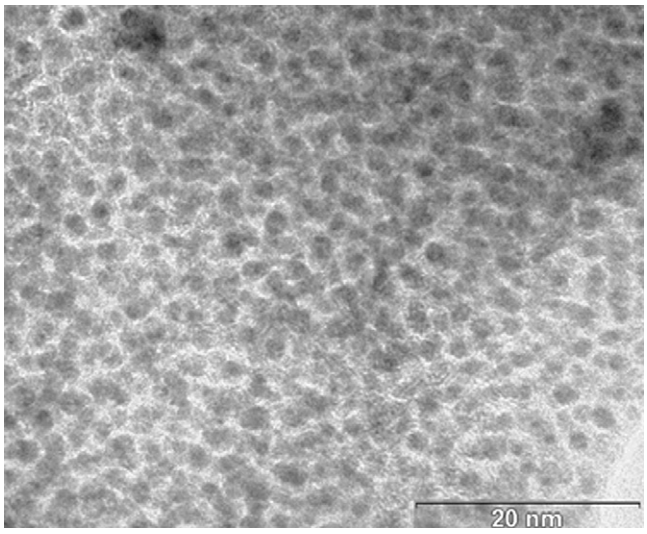


Figure 1. TEM micrograph of the nickel nanoparticles.

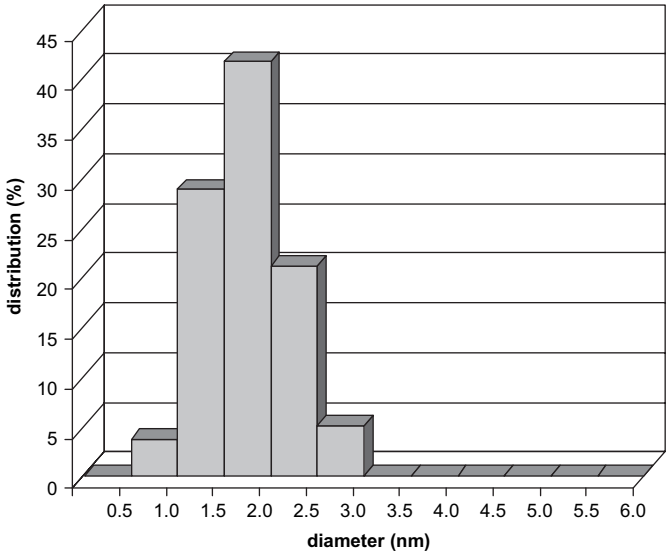
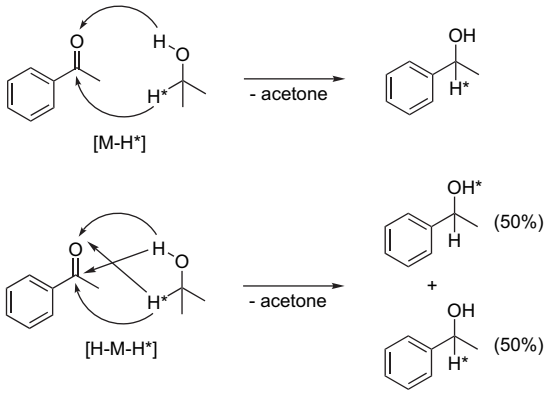


Figure 2. Size distribution of nickel nanoparticles determined by TEM. The sizes were determined for 220 nanoparticles selected at random.

be concluded that the presence of isopropanol at 76 °C has a beneficial effect in the generation of the nickel nanoparticles as regards their size and uniformity.

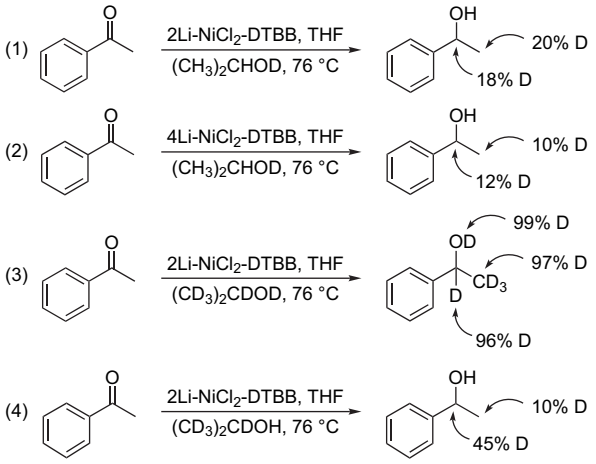
We were also interested in studying the reaction mechanism of the above processes. The hydrogen-transfer reduction mechanism of carbonyl compounds with isopropanol has been a subject of intense debate, especially in homogeneous catalysis,[8] which depends on every particular catalytic system. A Meerwein–Ponndorf–Verley-type mechanism[21] involves a direct hydrogen transfer through a six-membered transition state composed of the hydrogen acceptor, metal, and hydrogen donor, without the participation of metal hydride intermediates. The mechanism of hydrogen transfer from isopropanol to a ketone using the catalyst $RhCl(PPh_3)_3$ was extensively investigated.[22] An essential component for this reaction is potassium hydroxide, which was believed to be effective in removing a proton from the reacting complex during part of the



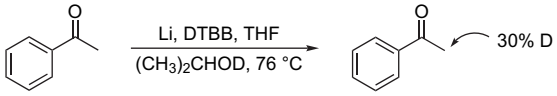
Scheme 1. The hydridic route for the transition-metal catalysed transfer hydrogenation with isopropanol.

catalytic cycle. Certainly, many other homogeneous catalyst systems using an alcohol as the hydrogen donor appear to need a base (KOH) for their reactivity. More recently, it is generally accepted that transition-metal catalysts operate through a hydridic route with two possible pathways (Scheme 1).[8c] In the monohydride mechanism, the hydride and the proton keep their identity, only the C–H hydrogen of the donor forming the hydride on the metal, while the O–H hydrogen adds to the carbonyl oxygen. In the dihydride mechanism, the two hydrogens of the donor become equivalent after being transferred to the metal to give the dihydride.

In the case of our transfer hydrogenation system with NiNPs the scenario is quite different, since the reaction is considered to take place under heterogeneous conditions. Nonetheless, we carried out a series of experiments with different deuterium labelled isopropanols that could provide any evidence about the reaction mechanism (Scheme 2). In experiment (1), isopropanol-OD was used, leading to a relatively low incorporation of D at the benzylic position and similar incorporation into the methyl group. Experiment (2) was carried out in order to see any effect of adding 2 mmol excess of lithium, which might generate molecular deuterium, under the same conditions as in experiment (1). In this case, the deuterium incorporation was relatively low at both the benzylic position



Scheme 2. Labelling experiments in the transfer hydrogenation of acetophenone.



Scheme 3.

and methyl group. In experiment (3), isopropanol-d_8 led to an almost quantitative incorporation of deuterium in all the reactive positions. Experiment (4) was carried out using isopropanol-2-d_1 providing 45% incorporation of deuterium at the benzylic position. It is worthy of note that deuterium incorporation at the OH was detected only in experiment (3). Up to 15% deuterium incorporation at the OH was detected for the reaction crudes in experiments (1)–(3). However, some OD–OH exchange during the purification by column chromatography over silica could account for these results.

From the above experiments it can be inferred that a hydrogen-transfer process from isopropanol is occurring, instead of alternative catalytic hydrogenation- or dissolving metal-type processes. Under the standard reaction conditions (in which no excess of lithium is used), small amounts of lithium isopropoxide can be generated, acting as a base and leading to some enolisation prior to the transfer hydrogenation. This process was demonstrated by reacting acetophenone with some lithium, DTBB and isopropanol-OD in THF at 76 °C (Scheme 3). The fact that the O–D deuterium is partially transferred to the carbonyl carbon atom [experiments (1) and (2), Scheme 2], is more in agreement with a dihydride-type mechanism. However, a fast H–D exchange between the acetophenone CH_3 group and the isopropanol-OD, together with a possible primary kinetic isotope effect, could account for a deuterium incorporation (18%) somewhat far from the theoretically expected (50%) at that position. Experiment (4) was more definitive in confirming a dihydride-type mechanism, since ~50% theoretical deuterium incorporation was achieved at the benzylic position. It must be clarified that dihydride species refer in this case to those resulting from the transfer of the two hydrogen atoms of the donor to the surface of the metal.

Finally, we also devised the possibility of re-utilisation of the NiNPs. Thus, once the reaction was stopped, the NiNPs were decanted and the supernatant removed, followed by the addition of more isopropanol and the substrate. Table 4 shows the recycling results after 1 h obtained for the reduction of acetophenone. The NiNPs could be re-used during four consecutive runs without any apparent loss of activity. It is noteworthy that although the yield dropped significantly from the fifth run, the amount of ethylbenzene formed (the major product obtained when using Raney Ni) was in all cases <5%. Therefore, we would expect better yields from the fifth run for longer reaction times than 1 h. These recycling experiments also demonstrate that, in contrast with most of the catalytic systems used for the transfer hydrogenation with isopropanol (either homogeneous or heterogeneous), the reduction with the NiNPs can proceed in the absence of a base. Consequently, the reaction system is simpler and avoids some undesired secondary reactions such as condensation reactions.

Table 4
Re-utilisation of NiNPs in the hydrogen-transfer reduction of acetophenone

Run	1	2	3	4	5	6	7
Yield[a] (%)	94	93	92	95	65	69	59

[a] GLC yield after 1 h.

3. Conclusion

Nickel(0) nanoparticles, prepared from nickel(II) chloride, lithium powder, and a catalytic amount of DTBB, have shown to promote readily the transfer hydrogenation with isopropanol of a variety of aromatic and aliphatic ketones and aldehydes in the absence of any added base at 76 °C. Modest-to-high yields of the corresponding alcohols were obtained, depending on the functional groups and/or the structure of the substrate. The reducing system showed to be diastereoselective for most of the cyclic ketones studied and superior to other forms of nickel under the same reaction conditions. Moreover, the nickel nanoparticles could be re-utilised several times, maintaining a high activity in a very simple reaction medium composed of the nickel nanoparticles, isopropanol and the substrate, without any added base. According to some deuteration experiments, the reaction seems to proceed through a dihydride-type mechanism. Efforts to stabilise the nickel nanoparticles and use them catalytically are under way.

4. Experimental

4.1. General

Flash column chromatography was performed using silica gel 60 of 40–60 μm. THF was directly used without any purification (Acros, 99.9%). Anhydrous nickel(II) chloride (Aldrich), lithium powder (MEDALCHEMY S. L.), isopropanol (Panreac, Acros), isopropanol-OD (Isotel), isopropanol-d_8 (Aldrich), and isopropanol-2-d_1 (Aldrich) were commercially available. All the starting materials were commercially available of the best grade (Aldrich, Acros, Alfa Aesar) and were used without further purification. TEM images were recorded using a JEOLJEM2010 microscope, equipped with a lanthanum hexaboride filament, operated at an acceleration voltage of 200 kV. A drop of the nickel nanoparticle suspension was added to a holey carbon-coated 300 mesh copper grid allowing the solvent to evaporate before being introduced into the microscope.

4.2. General procedure for the NiNPs-promoted transfer hydrogenation of carbonyl compounds

Nickel chloride (130 mg, 1 mmol) was added over a suspension of lithium (14 mg, 2 mmol) and DTBB (13 mg, 0.05 mmol) in dry THF (2 mL) at room temperature under argon. The reaction mixture, which was initially dark blue, changed to black, indicating that nickel(0) nanoparticles were formed. After 10 min, *i*-PrOH (4 mL) and the corresponding carbonyl compound (1 mmol) were consecutively added. The reaction mixture was warmed up to 76 °C and monitored by

GLC–MS until total or steady conversion of the starting material. The resulting suspension was diluted with diethyl ether (20 mL), filtered through a pad containing Celite, and the filtrate was dried over $MgSO_4$. The residue obtained, after removal of the solvent (15 Torr), was purified by column chromatography (silica gel, hexane/EtOAc) to give the corresponding pure alcohol.

1-Phenylethanol, 1-(4-trifluoromethyl)phenylethanol, 1-(4-methoxyphenyl)ethanol, 1-phenylbutanol, benzyl alcohol, 4-phenyl-2-butanol, dicyclohexylmethanol, 2-adamantanol, (±)-*exo*-2-norborneol,[23] β-oestradiol,[24] cyclohexanol, and (−)-menthol[25] were characterised by comparison of their physical and spectroscopic data with those of commercially available samples (Aldrich). 1-(3-Methoxyphenyl)ethanol,[26] 1-(4-tolyl)ethanol,[27] 1-(3-tolyl)ethanol,[28] 1,3-diphenyl-1-propanol,[29] 6-undecanol,[30] *trans*-4-*tert*-butylcyclohexanol,[31] (1*R**,4a*R**,8a*S**)-decahydro-1-naphthol,[32] 5α-androstane-3α,17α-diol and 5α-androstane-3α,17β-diol,[33] and *cis*-3,3,5-trimethylcyclohexanol,[34] were characterised by comparison of their physical and spectroscopic data with those described in the literature.

Acknowledgements

This work was generously supported by the Spanish Ministerio de Educación y Ciencia (MEC; grant no. CTQ2004-01261; Consolider Ingenio 2010-CSD2007-00006) and the Generalitat Valenciana (GV; grants no. GRUPOS03/135 and GV05/005). P.R. thanks the MEC for a predoctoral grant.

References and notes

1. For reviews, see: (a) *Comprehensive Organic Synthesis*; Trost, B. M., Fleming, I., Eds.; Pergamon: Oxford, 1991; Vol. 8, Chapters 1.1–1.8; (b) Hudlický, M. *Reductions in Organic Chemistry*, 2nd ed.; ACS: Washington, DC, 1996.
2. For reviews, see: (a) Johnstone, R. A. W.; Wilby, A. H. *Chem. Rev.* **1985**, *85*, 129–170; (b) Kellogg, R. M. *Comprehensive Organic Synthesis*; Trost, B. M., Fleming, I., Eds.; Pergamon: Oxford, 1991; Vol. 8, Chapter 1.3; (c) Bäckvall, J. E. *J. Organomet. Chem.* **2002**, *652*, 105–111; (d) *Hydrogen Transfer Reactions*; Hynes, J. T., Klinman, J. P., Limbach, H. H., Schowen, R. L., Eds.; Wiley-VCH: Weinheim, 2007.
3. For reviews, see: (a) Ohkuma, T.; Noyori, R. *Comprehensive Asymmetric Catalysis*; Jacobsen, E. N., Pfaltz, A., Yamamoto, H., Eds.; Springer: Berlin, 1999; Vol. I, pp 227–246; (b) Gladiali, S.; Mestroni, G. *Transition Metals for Organic Synthesis*; Beller, M., Bolm, C., Eds.; Wiley-VCH: Weinheim, 2004; Vol. 2, Chapter 1.3.
4. For a recent example, see for instance: Enthaler, S.; Jackstell, R.; Hagemann, B.; Junge, K.; Erre, G.; Beller, M. *J. Organomet. Chem.* **2006**, *691*, 4652–4659.
5. See for instance: Nindakova, L. O.; Shainyan, B. A.; Belogonova, L. N. *Russ. J. Org. Chem.* **2003**, *39*, 1484–1488.
6. See for instance: Wu, X.; Liu, J.; Li, X.; Zanotti-Gerosa, A.; Hancock, F.; Vinci, D.; Ruan, J.; Xiao, J. *Angew. Chem., Int. Ed.* **2006**, *45*, 6718–6722.
7. For reviews, see: (a) Noyori, R.; Hashiguchi, S. *Acc. Chem. Res.* **1997**, *30*, 97–102; (b) Ikariya, T.; Murata, K.; Noyori, R. *Org. Biomol. Chem.* **2006**, *4*, 393–406; (c) Gladiali, S.; Alberico, E. *Chem. Soc. Rev.* **2006**, *35*, 226–236.
8. (a) Noyori, R.; Yamakawa, M.; Hashiguchi, S. *J. Org. Chem.* **2001**, *66*, 7931–7944; (b) Clapham, S. E.; Hadzovic, A.; Morris, R. H. *Coord. Chem. Rev.* **2004**, *248*, 2201–2237; (c) Samec, J. S. M.; Bäckwall, J.-E.; Andersson, P. G.; Brandt, P. *Chem. Soc. Rev.* **2006**, *35*, 237–248.
9. Boldrini, G. P.; Savoia, D.; Tagliavini, E.; Trombini, C.; Umani-Ronchi, A. *J. Org. Chem.* **1985**, *50*, 3082–3086.
10. Le Page, M. D.; James, B. R. *Chem. Commun.* **2000**, 1647–1648.
11. Phukan, P.; Sudalai, A. *Synth. Commun.* **2000**, *30*, 2401–2405.
12. Upadhya, T. T.; Katdare, S. P.; Sabde, D. P.; Ramaswamy, V.; Sudalai, A. *Chem. Commun.* **1997**, 1119–1120.
13. Mohapatra, S. K.; Sonavane, S. U.; Jayaram, R. V.; Selvam, P. *Org. Lett.* **2002**, *24*, 4297–4300.
14. Mebane, R. C.; Mansfield, A. J. *Synth. Commun.* **2005**, *35*, 3083–3086.
15. (a) Alonso, F.; Calvino, J. J.; Osante, I.; Yus, M. *Chem. Lett.* **2005**, *34*, 1262–1263; (b) Alonso, F.; Calvino, J. J.; Osante, I.; Yus, M. *J. Exp. Nanosci.* **2006**, *1*, 419–433.
16. Alonso, F.; Yus, M. *Chem. Soc. Rev.* **2004**, *33*, 284–293.
17. (a) Alonso, F.; Osante, I.; Yus, M. *Adv. Synth. Catal.* **2006**, *348*, 305–308; (b) Alonso, F.; Osante, I.; Yus, M. *Tetrahedron* **2007**, *63*, 93–102.
18. Alonso, F.; Osante, I.; Yus, M. *Synlett* **2006**, 3017–3020.
19. Alonso, F.; Riente, P.; Yus, M. *Synlett* **2007**, 1877–1880.
20. Andrews, M. J.; Pillai, C. N. *Indian J. Chem., B* **1978**, *16*, 465–468.
21. For reviews, see: (a) de Graauw, C. F.; Peters, J. A.; van Bekkum, H.; Huskens, J. *Synthesis* **1994**, 1007–1017; (b) Nishide, K.; Node, M. *Chirality* **2002**, *14*, 759–767; (c) Cha, J. S. *Org. Process Res. Dev.* **2006**, *10*, 1032–1053; For a recent publication, see: (d) Yin, J.; Huffman, M. A.; Conrad, K. M.; Armstrong, J. D., III. *J. Org. Chem.* **2006**, *71*, 840–843.
22. Sharf, V. Z.; Freidlin, L. Kh.; Krutii, V. N. *Izv. Akad. Nauk SSSR, Ser. Khim.* **1977**, 735–739; *Chem. Abstr.* **1977**, *87*, 38552.
23. Diastereomeric ratio (^{1}H NMR): δ_H (CHO *exo*-norborneol) 3.76 ppm; δ_H (CHO *endo*-norborneol) 4.24 ppm.
24. Diastereomeric ratio (^{1}H NMR): δ_H (OH β-oestradiol) 4.50 ppm; δ_H (OH α-oestradiol) 4.34 ppm.
25. Diastereomeric ratio (^{1}H NMR): δ_H (CHO menthol) 3.40 ppm; δ_H (CHO isomenthol) 3.80 ppm; (CHO neomenthol) 4.10 ppm.
26. Ookawa, A.; Kitade, M.; Soai, K. *Heterocycles* **1988**, *27*, 213–216.
27. *Dictionary of Organic Compounds*, 5th ed.; Buckingham, J., Ed.; Chapman and Hall: New York, NY, 1987; p 408; 1st suppl.
28. Ref. 27, p 407.
29. Alonso, F.; Yus, M. *Tetrahedron* **1998**, *54*, 1921–1928.
30. *Dictionary of Organic Compounds*, 5th ed.; Buckingham, J., Ed.; Chapman and Hall: New York, NY, 1982; Vol. 5, p 5662.
31. Abraham, R. J.; Byrne, J. J.; Griffiths, L.; Pérez, M. *Magn. Reson. Chem.* **2006**, *44*, 491–509; Diastereomeric ratio (^{1}H NMR): δ_H (CHO *trans*-4-*tert*-butylcyclohexanol) 3.52 ppm; δ_H (CHO *cis*-4-*tert*-butylcyclohexanol) 4.03 ppm.
32. Di Maio, G.; Mascia, M. G.; Vecchi, E. *Tetrahedron* **2002**, *58*, 3313–3318; Diastereomeric ratio (^{1}H NMR): δ_H [$CH_{eq}O$ (1*R**,4a*R**,8a*S**)-decahydro-1-naphthol] 3.74 ppm; δ_H [($CH_{ax}O$ (1*S**,4a*R**,8a*S**)-decahydro-1-naphthol] 3.15 ppm.
33. *Dictionary of Organic Compounds*, 5th ed.; Buckingham, J., Ed.; Chapman and Hall: New York, NY, 1982; Vol. 1, p 353; Diastereomeric ratio (^{1}H NMR): δ_H (CHO 5α-androstane-3α,17β-diol) 3.62 ppm; δ_H (CHO 5α-androstane-3α,17α-diol) 3.72 ppm.
34. Eliel, E.; Haubenstock, H. *J. Org. Chem.* **1961**, *26*, 3504–3506; Diastereomeric ratio (^{1}H NMR): δ_H (CHO *cis*-3,3,5-trimethylcyclohexanol) 3.77 ppm; δ_H (CHO *trans*-3,3,5-trimethylcyclohexanol) 4.21 ppm.