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Iridium-supported catalyst for enantioselective hydrogenation of 1-phenyl-1,2-propanedione: The effects of the addition of promoter and the modifier concentration

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Abstract

The enantioselective hydrogenation of 1-phenyl-1,2-propanedione at 298 K and 40 bar over modified iridium-supported catalysts has been studied, using cinchonidine as modifier. The catalysts were prepared by impregnation of $Ir(acac)_3$ on two different supports: SiO_2 and TiO_2, followed by calcination in air and reduction under hydrogen flow at 773 K. The effects produced by the reduction temperature (473 and 773 K) and the effect of the addition of promoters (CeO_2 and MoO_3) on catalyst surface properties were studied in Ir/TiO_2 catalysts. All the samples were characterized by nitrogen adsorption–desorption isotherms at 77 K, H_2 chemisorption, XRD, TEM, XRD and XPS. In some cases, there was an enhancement in the reaction rate when $Ir^{\delta+}$ species were in the catalysts. The effect of the chiral modifier concentration was also studied and the results revealed a bell-type curve dependence of the enantiomeric excess with the modifier concentration.

Keywords: Ir; 1-Phenyl-1,2-propanedione; Cinchonidine; Hydrogenation; Enantioselectivity

1. Introduction

The hydrogenation of 1-phenyl-1,2-propanedione has been rarely studied in spite of the important applications of one of its partially hydrogenated product. The (*R*)-1-phenyl-1-hydroxy-2-propanone, also known as L-(−)phenylacetyl-)phenylacetylcarbinol (L-PAC) or Neuberg's ketol (90-63-1) or 1-hydroxy-1-phenylacetone, acts as a key intermediate for the synthesis of L-ephedrine, pseudoephedrine, norephedrine, norpseudoephedrine as well as adrenaline, amphetamine, methamphetamine, phenylpropanolamine and phenylamine. L-PAC can be produced by chemical synthesis from cyanohydrins, but the biotransformation route for its production from benzaldehyde is the present industrial preference [1]. Still, heterogeneous catalysts are a very attractive and interesting proposal due to their advantage in large-scale operations: they are easy to use and can be easily separated from reactants and products.

Salmi's group studied the effect of cinchonidine concentration, the reaction temperature, the nature of the solvent (ethanol, ethyl acetate and dichloromethane) and the reduction temperature of the catalysts in the enantioselective hydrogenation of 1-phenyl-1,2-propanedione over Pt/Al_2O_3 catalysts [2,3]. The most effective catalyst in terms of activity and enantioselectivity was obtained by in situ modification in dichloromethane yielding to 67 mole% of (*R*)-1-phenyl-1-hydroxy-2-propanone, corresponding to the enantiomeric excess of 64% where the enantiomeric excess is independent of the reactant conversion [4]. In the same report, the authors pointed out that the hydrogenation rate was higher with the Pt/C catalyst than with Pt/Al_2O_3 in a mixture of solvents, ethanol and acetic acid, although the enantiomeric excesses (e.e.) was lower (17 and 33%, respectively). A beneficial effect on the e.e. was produced when acetic acid is added to the reaction mixture in ethanol, where the e.e. is 24% without acetic acid and increases up to

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33% with the addition of acetic acid. This reaction was studied also in Pt/SiO_2 fibres [3], and the results indicate that the hydrogenation rate was lower than the alumina-supported Pt catalyst, displaying an e.e. of 50% to (*R*)-1-phenyl-1-hydroxy-2-propanone. Additionally, the use of Pt on mesoporous MCM-41 in the enantioselective hydrogenation of 1-phenyl-1,2-propanedione was successfully demonstrated. Toukoniitty et al. [5] have studied three different metal contents (5, 10 and 15 wt.%) of Pt on MCM-41 modified with (−)-cinchonidine (CD), obtaining a maximum enantiomeric excess of (*R*)-1-phenyl-1-hydroxy-2-propanone close to 44% using the 15 wt.% Pt/MCM-41 catalyst. This behaviour was attributed to the larger metal Pt particles displayed by this catalyst. Similar results in terms of activity and enantioselectivity were obtained by Reyes and co-workers [6] in the same reaction using 1 wt.% Pt/MCM-41. The observed behaviour has been attributed to confinement effects produced in the hexagonal channel of the MCM-41.

The aim of the present work is to study the enantioselective hydrogenation of 1-phenyl-1,2-propanedione on Ir-supported catalysts in the presence of cinchonidine as chiral inducer. The effect of the addition of ceria and molybdenum oxide promoters on two different supports (SiO_2 and TiO_2) on the activity and the enantioselectivity to (*R*)-1-phenyl1-1-hydroxy-2-propanone is studied. A scheme of the studied reaction is shown in Fig. 1.

2. Experimental

The catalysts were prepared by wet impregnation of the support (SiO_2 BASF D-11-11 and TiO_2 P 25 Degussa). An acetone solution of iridium acetylacetonate in an appropriate amount to get 1 wt.% of Ir was used to impregnate the support. The required amount of ammonium heptamolybdate or cerium(III) nitrate was used to get 1 wt.% of the promoter expressed as % of CeO_2 and MoO_3. The solids were calcined in air at 573 K and reduced in flowing H_2 at 573 K (LT) or 773 K (HT), prior the catalytic evaluation or characterisation.

The hydrogenation in liquid phase of 1-phenyl-1,2-propanedione was carried out in a stainless steel batch reactor at 298 K and a hydrogen pressure of 40 bar. The hydrogen pressure was kept constant during the reaction. In the enantioselective hydrogenation reactions using cinchonidine as a modifier, the premixing method was used. The powdered catalyst was reduced in H_2 flow at 773 K, and then the catalyst dispersed in the solvent was fed to the reactor and stabilized at the reaction temperature, 298 K under nitrogen flow. Subsequently, the modifier, substrate and the remaining solvent were added into the reactor. The stirring speed was keeping constant at 900 rpm. Then, hydrogen was flashed to the reactor at atmospheric pressure to remove the inert gas and then pressurized up to 40 bar. The solvent used in this study was cyclohexane (GR for analysis-Merck). In all the standard

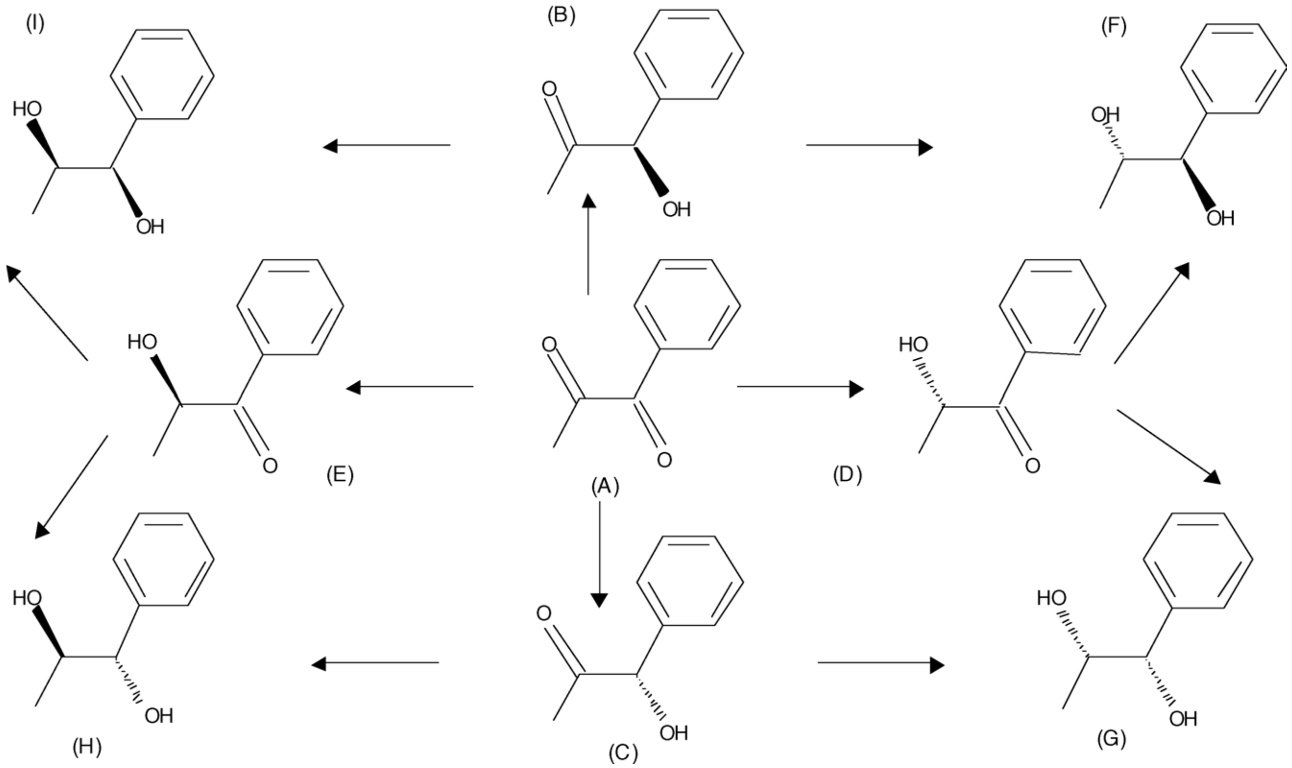

Fig. 1. Reaction scheme for hydrogenation of: (A) 1-phenyl-1,2-propanedione; (B) (*R*)-1-phenyl-1-hydroxy-2-propanone; (C) (*S*)-1-phenyl-1-hydroxy-2-propanone; (D) (*R*)-1-phenyl-1-keto-2-propanol; (E) (*S*)-1-phenyl-1-keto-2-propanol; (F) (1*R*,2*S*)-1-phenyl-1,2-propanediol; (G) (1*R*,2*R*)-1-phenyl-1,2-propanediol; (H) (1*S*,2*R*)-1-phenyl-1,2-propanediol; (I) (1*S*,2*S*)-1-phenyl-1,2-propanediol.

experiments, the volume of solvent in the pressured batch reactor was 50 mL, the cinchonidine and 1-phenyl-1,2-propanedione concentrations were 3.4×10^{-4} and 1×10^{-2} M, respectively, and the weight of the catalyst was 100 mg. To study the effect of the modifier, the CD concentration was varied in the range 1×10^{-4} to 1×10^{-3} M. Samples were taken periodically from the reactor and analysed by using a gas chromatograph-mass spectrometer (GCMS-QP5050 Shimadzu) provided with a chiral β-dex 225 column (30 m; Supelco). During the catalytic reaction, no side reactions, such as solvent dehydrogenation or hydrogenolisis reactions, were detected. A scheme of the reaction is presented in Fig. 1. The e.e. of (*R*)-1-phenyl-1-hydroxy-2-propanone and regioselectivity (r.s.) are defined as:

$$\text{e.e.} = \frac{[B]-[C]}{[B]+[C]} \times 100\% \quad \text{and} \quad \text{r.s.} = \frac{[B]+[C]}{[D]-[E]} \times 100\%$$

where B = (*R*)-1-phenyl-1-hydroxy-2-propanone; C = (*S*)-1-phenyl-1-hydroxy-2-propanone; D = (*R*)-1-phenyl-1-keto-2-propanol; E = (*S*)-1-phenyl-1-keto-2-propanol.

Catalyst characterization was carried out using the following techniques: the temperature-programmed reduction of the catalysts (TPR) was studied in a TPR/TPD 2900 Micromeritics system equipped with a thermal conductivity detector. The catalysts were reduced in a 5%H_2/Ar mixture (40 $cm^3 min^{-1}$), using a heating rate of 10 K min^{-1} from room temperature up to 873 K. The specific area was evaluated from the adsorption of N_2 at 77 K in an automatic Micromeritics system Model ASAP 2010. The hydrogen chemisorption experiments at room temperature were performed in a pressure range 1–400 mbar, followed by a second adsorption isotherm of H_2 after outgassing at room temperature in the same equipment. The amount of hydrogen irreversibly adsorbed was obtained by subtracting both isotherms. X-ray diffraction (XRD) patterns were obtained on a Rigaku diffractometer using a Ni filter and Cu $K\alpha_1$ radiation. Intensity was measured by scanning steps in the 2θ range between 3° and 70° at 1° min^{-1}. TEM studies were carried out by using a Jeol Model JEM-1200 EXII System. XPS studies were recorded using a Escalab 200R spectrometer provided with a hemispherical analyser, operated in a constant pass energy mode and non-monochromatic Mg Kα X-ray radiation ($h\nu = 1253.6$ eV) operated at 10 mA and 12 kV. The system was provided with a reaction cell, which allows pre-treatment at high temperatures. The catalysts were reduced in situ in hydrogen at 773 K for 2 h and then transported to the analysis chamber without air contact. The surface Ir/Si, Ir/Ti and Ir/Mo were estimated from the integrated intensities of Ir $4f_{7/2}$, Si 2p, Ti 2p and Mo 3d lines after background subtraction and corrected with the atomic sensitivity factors [7]. The line of Si 2p at 103.4 eV and or C 1s at 284.9 eV were used as an internal standard. Ir 4f peaks were decomposed into several components assuming that the peaks had Gaussian–Lorentzian shapes.

3. Results and discussion

Table 1 summarizes the H/Ir ratios obtained from chemisorption and the metal particle size evaluated from TEM micrographs for the studied catalysts. The non-promoted Ir/TiO_2 reduced at low temperatures LT (473 K) and Ir/SiO_2 HT displayed the highest H/Ir ratios (0.68 and 0.43, respectively) indicative of high dispersed metallic catalysts. After a high temperature reduction treatment, the Ir/TiO_2 sample (HT) displayed a significant decrease in the hydrogen uptake ability. This change cannot be attributed to a sintering of the metal crystallites, but is a result of a partial surface coverage of Ir surface atoms by TiO_x species generated upon the reduction of the solids at high temperature, due to the so called SMSI effect, leading to a surface decoration of metal crystals. This behaviour is also supported by TEM results. The addition of a promoter to the Ir catalysts also produces a drop in the H/Ir ratio, which can be attributed to promoter oxide coverage of the metal crystals. This effect is even more significant at higher reduction temperature due to the fact that partially reduced CeO_{2-x} or MoO_{3-x}, generated during the reduction treatment, can easily migrate and decorate the Ir crystals. For the Ir/SiO_2 HT catalyst, which does not present the SMSI effect, the metal particle size estimated by chemisorption and TEM are in good agreement.

Fig. 2 displays the TPR profiles of the studied catalysts. The Ir/SiO_2 sample shows a single reduction peak centred at 357 K, which is attributed to the reduction of iridium oxide. The reduction profile exhibited by the Ir/TiO_2 sample is more complex; the reduction of iridium species appears at 384 K and a partial reduction of the support begins to be produced at temperatures close to 450 K, overlapping with the reduction of isolated iridium oxides patches, whose peak is centred at 506 K. The observed shift in the reduction temperature can be attributed to the strong interaction between the support and metal particles in the so-called SMSI effect.

The reduction profiles of the promoted catalysts are very complex. The Ir-Ce/SiO_2 catalyst shows a peak at 498 K with two shoulders corresponding to partial reduction of Ir by the presence of Ce. With regard to the Ir-Ce/TiO_2 and Ir-Mo/TiO_2 samples, the profiles exhibit certain similarities with those previously described for Ir-Ce/SiO_2, but with

Table 1
H/Ir ratio obtained from chemisorption and Ir particle size derived from TEM studies of Ir-supported catalysts

Catalyst	H/Ir	*d* (Å)
Ir/TiO_2 LT	0.68	13
Ir-Ce/TiO_2 LT	0.21	17
Ir-Ce/SiO_2 LT	0.07	20
Ir/TiO_2 HT	0.10	21
Ir-Ce/TiO_2 HT	0.02	21
Ir-Mo/TiO_2 HT	0.02	20
Ir/SiO_2 HT	0.43	17
Ir-Ce/SiO_2 HT	0.04	20

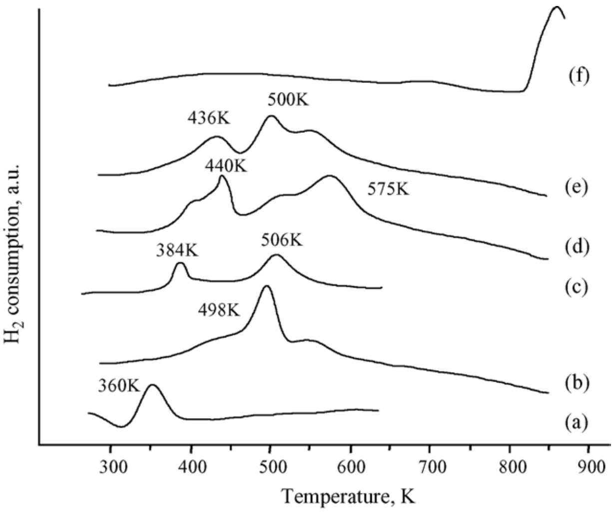

Fig. 2. TPR profiles of Ir-supported catalysts: (a) Ir/SiO_2; (b) Ir-Ce/SiO_2; (c) Ir/TiO_2; (d) Ir-Ce/TiO_2; (e) Ir-Mo/TiO_2; (f) MoO_3.

higher hydrogen consumption, which is probably due to the partial reduction of the support. Additionally, the TPR profiles of the MoO_3 show that the reduction of the pure MoO_3 takes place at higher temperatures. These results suggest that under reduction conditions in most of the studied systems, Ir remains as Ir^0 and $Ir^{\delta+}$ species, whereas the promoters are partially reduced. XPS analyses also support these findings.

Surface studies of the reduced catalysts were performed by XPS. It was found that in the Ir/SiO_2 HT catalysts, the metal component is present essentially as Ir^0 (Ir $4f_{7/2}$ core level centred at 60.2 eV), whereas the promoted Ir-Ce/SiO_2 displays only a slight shift (60.4 eV). This result may suggest the presence of a small fraction of $Ir^{\delta+}$ species generated from the electronic transfer between the partially reduced cerium oxide and iridium particles. With regard to The Ir/TiO_2 series, a summary of the obtained Ir $4f_{7/2}$ core-level of the reduced catalysts is given in Fig. 3. Ir/TiO_2 LT displays the Ir $4f_{7/2}$ peak at 60.3 eV, while in the HT counterpart the signal appears at 60.5 eV. This shift is a consequence of a partial oxidation of iridium crystals, essentially in the metal support interphase, induced by TiO_x species migration onto the metal component. A similar effect is produced by the addition of a promoter, oxide cerium or molybdenum oxides, either at low or high reduction temperatures. In these samples, the BE of the Ir $4f_{7/2}$ is centred in the range 60.5–60.6 eV. Table 2 summarizes the BE of Ir $4f_{7/2}$, Ti $2p_{3/2}$, Si 2p, Ce $3d_{5/2}$ and Mo $3d_{5/2}$ for the

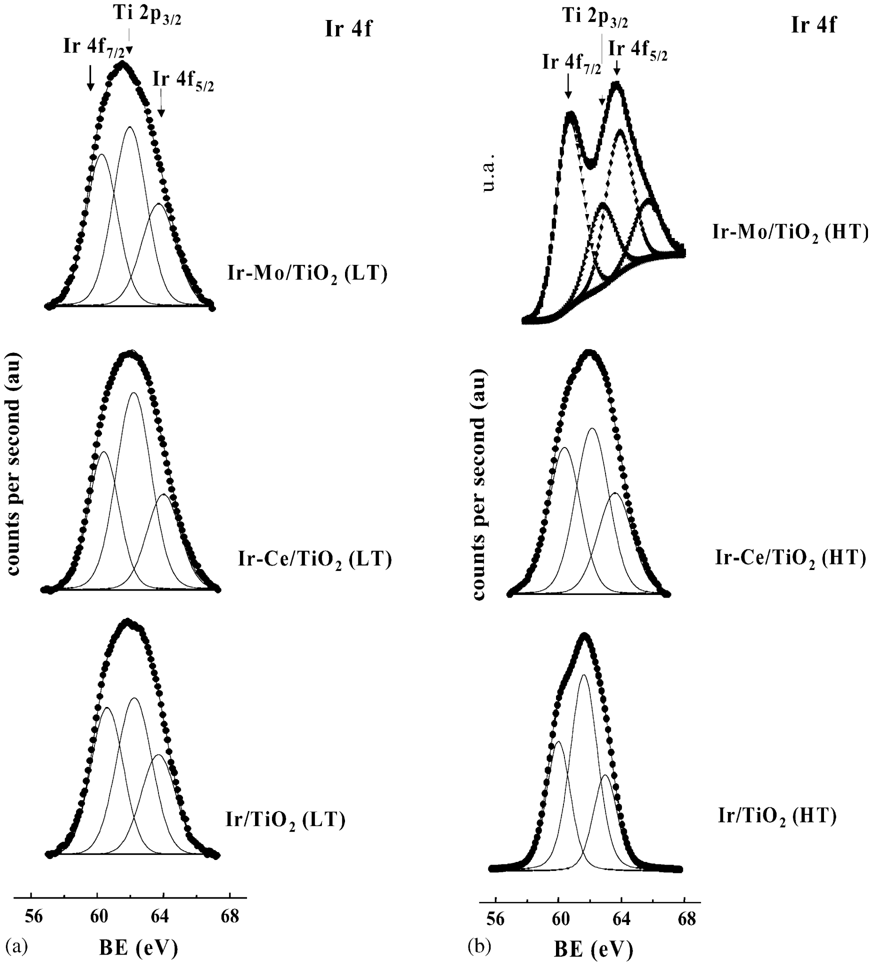

Fig. 3. Ir 4f core level spectra of Ir/TiO_2-reduced catalysts: (a) LT series; (b) HT series.

Table 2
Binding energies for Ir $4f_{7/2}$, Ti $2p_{3/2}$, Si 2p, Ce $3d_{5/2}$ and Mo $3d_{5/2}$ of reduced Ir-supported catalysts

Catalyst	Ir $4f_{7/2}$ (eV)	Ti $2p_{3/2}$ (eV)	Si 2p (eV)	Ce $3d_{5/2}$ (eV)	Mo $3d_{5/2}$ (eV)
Ir/TiO_2 LT	60.2	–	–		
Ir-Ce/TiO_2 LT	60.5	458.5	–	882.8	–
Ir-Mo/TiO_2 LT	60.5	458.5	–	–	231.8
Ir/TiO_2 HT	60.6	458.5	–		
Ir-Ce/TiO_2 HT	60.4	458.4	–	882.8	–
Ir-Mo/TiO_2 HT	60.6	458.5	–	–	231.6
Ir/SiO_2 HT	60.3	–	103.4	–	–
Ir-Ce/SiO_2 HT	60.5	–	103.4	882.6	–

studied catalysts. The BE of Si 2p and Ti $2p_{3/2}$ peaks are the expected values for the corresponding SiO_2 and TiO_2 oxides. In the later, no shift was detected in the BE after high temperature reduction even when considering that enough evidence of a partial reduction exists. Conversely, in the Ce $3d_{5/2}$ and Mo $3d_{5/2}$ core level spectra, important changes suggest an increasing proportion of Ce_2O_3 and MoO_2 as the reduction temperature increases.

The Ir/Si atomic surface ratios derived from XPS data is lower in the Ir-Ce/SiO_2 in comparison with the Ir/SiO_2 catalysts, which was expected considering that the Ir crystals are partially covered by cerium oxide species. In the Ir/TiO_2 catalysts, the Ir/Ti ratio decreases slightly in the LT series with the addition of the promoters (Ce or Mo oxides); however, in the HT series, the drop is more significant in the Ir-Mo catalysts. As discussed previously, the surface coverage of Ir species by partially reduced species of the promoter and the support may account for the observed behaviour. The higher mobility of MoO_x moieties generated with catalyst reduction at high temperature when compared with the CeO_x explains the larger decreases in the Ir/Ti ratio. Table 3 compiles the atomic surface ratios of the studied catalysts.

XRD studies of the different catalysts detected only the lines attributed to the support TiO_2 (anatase and rutile, the former in higher proportion), whereas no lines were observed in SiO_2, an amorphous support. This was expected considering the low metal and promoter loading.

3.1. Support effect

Many studies have presented evidence indicating the importance of the support because it affects both the activity and the enantioselectivity in the hydrogenation of many reactions. Indeed, the effect of the support on the catalytic performance in the hydrogenation of ethyl pyruvate over silica, alumina, active charcoal and zeolite-supported Pt catalysts [6,8] using cinchonidine as modifier has been studied. The reported results revealed that the support itself has only a slight effect on the reaction, although it strongly affects the metal dispersion. The metal particle size has a great influence not only on the activity but also on the selectivity. Thus, for Pt catalysts used in the hydrogenation of ethyl pyruvate, relatively large Pt particle with dispersion lower than 50% have produced the best results [9].

Table 3
The Ir/M atomic surface ratio (M = Si, Ti, Ce or Mo) of Ir-supported catalysts

Catalyst	Ir/Ti (Si)	Ir/Ce	Ir/Mo	Ce/Ti (Si)	Mo/Ti (Si)
Ir/TiO_2 LT	0.029	–	–	–	–
Ir-Ce/TiO_2 LT	0.022	0.846	–	0.026	–
Ir-Mo/TiO_2 LT	0.026	–	0.448	–	0.058
Ir/TiO_2 HT	0.027	–	–	–	–
Ir-Ce/TiO_2HT	0.026	0.702	–	0.037	–
Ir-Mo/TiO_2 HT	0.010	–	0.204	–	0.049
Ir/SiO_2 HT	0.042	–	–	–	–
Ir-Ce/SiO_2 HT	0.036	0.389	–	0.014	–

Similar studies on other reactions have also been performed. In the hydrogenation of 1-phenyl-1,2-propanedione, Toukoniitty et al [4] studied two different commercial catalysts, 5%-Pt/C and 5%-Pt/Al_2O_3, with 1.5 and 8.3 nm mean metal particle size, respectively. The hydrogenation rate was higher with the Pt/C catalysts than over Pt/Al_2O_3, but the e.e. of (*R*)-1-phenyl-1-hydroxy-2-propanone was lower with the Pt/C catalysts that Pt/Al_2O_3. The low e.e. obtained over Pt/C catalysts was attributed to the smaller average Pt particle size. These results are in agreement with others already reported [4] that the larger the metal particle size, the higher the enantioselectivity. This behaviour has been essentially attributed to a minimum ensemble required for an appropriate modifier adsorption otherwise only small fraction of the cinchonidine exhibits the required conformer to induce the reaction towards the desired enantiomer.

Fig. 4 compares the activity expressed as the evolution of the conversion level on time during hydrogenation of

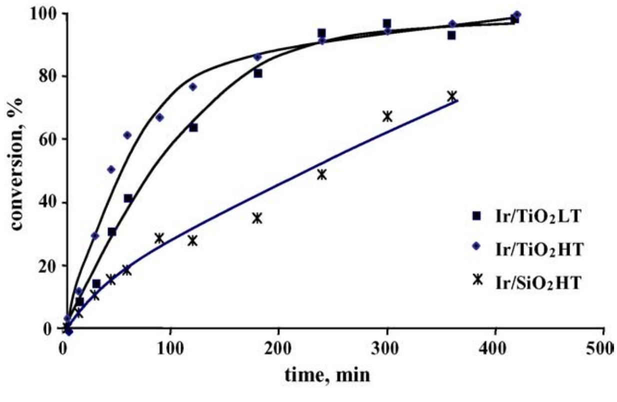

Fig. 4. Hydrogenation of 1-phenyl-1,2-propanodione over Ir catalysts at 40 bar and 298 K. Evolution of the conversion over time. Support effect.

Table 4
Initial reaction rate, constant kinetic rates, enantioselectivity and regioselectivity exhibited by Ir catalysts in the hydrogenation of 1-pheny-1,2-propanodione

Catalyst	$r_0 \times 10^5$ (mole (g min)$^{-1}$)	k_1 (min^{-1})	k_2 (min^{-1})	e.e.$_{max}$ (%)	r.s.$_{max}$ (%)	Yield$_{max}$ (%)	e.e.$_{50\%}$ (%)
Ir/TiO_2 LT	2.4	0.0113	0.0194	18	240	27	16
Ir-Ce/TiO_2 LT	6.8	0.5437	0.0869	21	310	35	18
Ir-Mo/TiO_2 LT	2.3	0.0632	0.4292	18	240	29	15
Ir-Ce/SiO_2 LT	1.1	0.0670	0.3081	22	300	19	19
Ir/TiO_2 HT	4.9	0.2823	0.4654	36	290	24	22
Ir-Ce/TiO_2 HT	1.5	0.0540	0.5033	31	350	28	14
Ir-Mo/TiO_2 HT	3.1	0.0964	0.3980	24	290	28	20
Ir/SiO_2 HT	1.8	0.0585	0.3413	47	280	18	30
Ir-Ce/SiO_2 HT	1.8	0.0550	0.3027	24	380	17	20

Reaction conditions: $T = 298$ K, $P = 40$ bar, [1-phenyl-1,2-propanedione] = 10^{-2} M, [CD] = 3.4×10^{-4} M, catalyst = 100 mg and 50 mL of solvent (cyclohexane).

1-phenyl-1, 2-propanedione on Ir/SiO_2 HT and Ir/TiO_2 LT and HT. Significant differences in activity may be observed, where the activity is lower in the former catalyst. Taking into account that the metal particle size of these catalysts is rather similar, the observed behaviour cannot be assigned to a particle size effect. However, one of the main differences in the properties of these samples is the oxidation state of the metal component. In the former, Ir exists as zero valence state, whereas in the Ir/TiO_2 HT, the presence of both Ir^0 and $Ir^{\delta+}$ species were suggested by the shift in the BE. Due to the presence of a signal due to Ti 3s between the Ir $4f_{7/2}$ and $4f_{5/2}$ peaks, a confidence deconvolution of the curve cannot be performed and consequently the fraction of partially oxidised Ir species cannot be estimated. Similar enhancement in activity is displayed by Ir/TiO_x catalysts in the hydrogenation of α, β unsaturated aldehydes as previously reported [10,11]. The presence of TiO_x species decorating the metal particles has been suggested as the active site for this later reaction, in which the site allows the polarization of the C=O bond. Considering the nature of the substrate, it is likely that the same kind of effect is occurring during the diketones hydrogenation. With regard to the enantioselectivity of this reaction, it was found that slight changes occurs in the e.e. as the conversion level increases reaching a maximum e.e. of the (*R*)-1-phenyl-1-hydroxy-2-propanone in the range of 20–35% under standard conditions. Even though these values may be considered as only a modest enantioselectivity, it has been pointed out that the studied reaction can be classified as a reaction with difficulty to induce enantioselectivity [12] because the substrate has an aromatic ring that provides the diketone with a higher ability to be adsorbed on metallic sites, and therefore, a competitive adsorption with the modifier can limit the fraction of modified sites and consequently the enantioselectivity. Taking into account that the substrate has two carbonyl bonds, the formation of the other couple of enantiomers, (*R*)-1-phenyl-1-keto-2-propanol and (*S*)-1-phenyl-1-keto-2-propanol, labelled as D and E, respectively, in the reaction scheme, may also occur. However, due to the presence of the aromatic ring, they are obtained to a lower extent as shown in Table 4. The regioselectivities are in the range of 250–300 for the Ir/SiO_2 and Ir-TiO_2 catalysts, slightly lower than those values displayed by the promoted-Ir catalysts. Moreover, the over hydrogenation of the (*R*) or (*S*)-1-phenyl-1-hydroxy-2-propanone and (*R*) or (*S*)-1-phenyl-1-keto-2-propanol may lead to the corresponding diol. Fig. 5 shows a product distribution during the hydrogenation reaction on one of the studied catalysts, Ir/TiO_2 HT. It can be observed that as the diketone is converted, the hydrogenation of both carbonyl bonds may occur; however, the hydrogenation of the C=O bond closer to the aromatic ring is favoured. Additionally, after 120 min of reaction, the slight formation of diols was observed using this catalyst.

3.2. Effect of the addition of promoters

The addition of promoters such as cerium oxides to Ir/SiO_2 and Ce and Mo oxides to Ir/TiO_2 catalysts was also studied. The presence of Ce in the Ir/SiO_2 catalyst produces a slight increase in both the activity and the enantioselec-

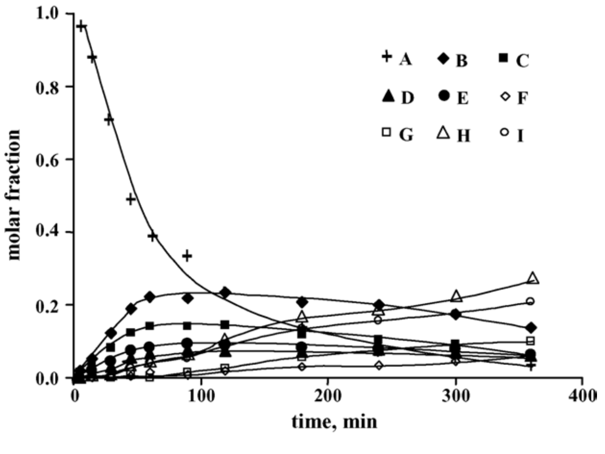

Fig. 5. The hydrogenation kinetic of 1-phenyl-1,2-propanedione in cyclohexane over Ir-Ce/TiO_2 LT at 298 K and 40 bar: (A) (+) 1-phenyl-1,2-propanedione; (B) (◆) (*R*)-1-phenyl-1-hydroxy-2-propanone; (C) (■) (*S*)-1-phenyl-1-hydroxy-2-propanone; (D) (▲) (*R*)-1-phenyl-1-keto-2-propanol; (E) (●) (*S*)-1-phenyl-1-keto-2-propanol; (F) (◇) (1*R*,2*S*)-1-phenyl-1,2-propanediol; (G) (□) (1*R*,2*R*)-1-phenyl-1,2-propanediol; (H) (△) (1*S*,2*R*)-1-phenyl-1,2-propanediol; (I) (○) (1*S*,2*S*)-1-phenyl-1,2-propanediol.

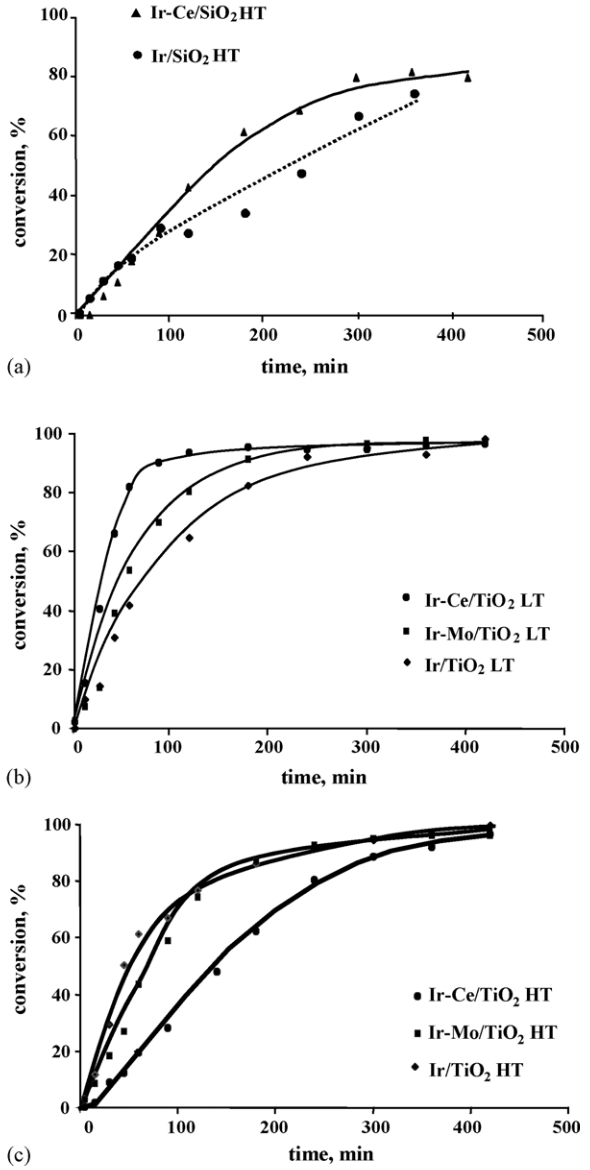

Fig. 6. Hydrogenation of 1-phenyl-1,2-propanodione over Ir catalysts at 40 bar and 298 K. Evolution of the conversion over time (a) effect of the promoter on Ir/SiO_2 catalyst, (b) effect of the promoters on Ir/TiO_2 LT catalysts and (c) effect of the promoter on Ir/TiO_2 HT catalysts.

tivity (see Fig. 6a). These small changes may be explained considering that the cerium oxide species are mainly adsorbed on the silica support; therefore, the Ir crystals are only slightly modified, as H_2 chemisorption results revealed.

Fig. 6b displays the evolution of the 1-phenyl-1,2-propanodione conversion over time for the Ce- or Mo-promoted Ir/TiO_2 LT. It can be seen that promoter presence contributes to an important increase in the activity in comparison with the Ir/TiO_2 LT catalyst. This increase is more significant than that observed in the Ir/SiO_2 counterpart, where even the decreases in the H/Ir ratio of the former is comparable to those of the Ir-Ce and Ir-Mo/TiO_2. This behaviour may be understood considering that both the support and the promoter contribute to the formation of the $Ir^{\delta+}$ species that are responsible for carbonyl bond polarisation and reaction rate enhancement. On the other hand, the e.e. referred to the (*R*)-1-phenyl-1-keto-2-propanol is slightly higher than that displayed by the Ir/TiO_2 LT catalysts, whereas the regioselectivity maintains high values. Indeed, high regioselectivity (r.s.) values were achieved in all of catalysts (see Table 4).

The Ce-Ir and Mo-Ir/TiO_2 HT catalysts showed lower activity compared to the Ir/TiO_2 sample. This behaviour is not unusual and can be attributed to a migration of both the precursor oxides and the TiO_x moieties on the metal particles, producing a partial coverage as well as the destruction of surface interfacial sites. This feature was previously reported for the hydrogenation of citral (an α, β unsaturated aldehyde) on Fe-Ir/TiO_2 HT catalysts [11]. In spite of a decrease in the activity, an enhancement in the enantioselectivity and regioselectivity in this series is observed. Assuming that as the metallic sites remain mainly covered by oxide species, this fact may be explained by the limited adsorption of diketone since the cinchonidine is preferentially adsorbed because it is more unsaturated than the substrate. Thus, the interaction between the adsorbed modifier and the diketone is enhanced, and therefore, the e.e. increases. High r.s. values were achieved in all of catalysts (see Table 4). These values are much higher than those previously reported [4] for the same kind of reaction conducted on Pt catalysts, and it is because Ir catalysts display a low activity for the hydrogenation of 2-hydroxy ketones. Additionally, under the studied conditions, the hydrogenation of both C=O groups to produce diols was low, contrasting with Toukoniitty's results [4,13]. This is one of the principal advantages of the Ir-modified supported catalysts.

Table 4 summarizes the catalytic results, including the initial reaction rate (expressed as mole of the diketone converted per minute per gram of catalyst), the e.e. at constant conversion level (50%) and the maximum e.e. achieved. The hydrogenation of the 1-phenyl-1,2-propanodione, as for most diketones and esters, is usually assumed as a first order dependence with respect to the reactant and in agreement with the kinetic studies achieved by Margitfalvi et al. [14] for the enantioselective hydrogenation of ethyl pyruvate. The first order plots showed, as in previous reports, two segments leading to k_1 and k_2 constant rates. This behaviour is explained in terms of other interactions taking place during the catalytic reactions such as solvent-intermediates, surface–intermediates interactions and also the possibility of dimerization of the cinchonidine, leading to $(CD)_2$ species which do not actively induce enantioselectivity [14].

3.3. Effect of the modifier concentration

In order to improve the enantioselectivity for a given system, a study of the effect of the modifier concentration appears relevant. Margitfalvi et al. [15] have reported that

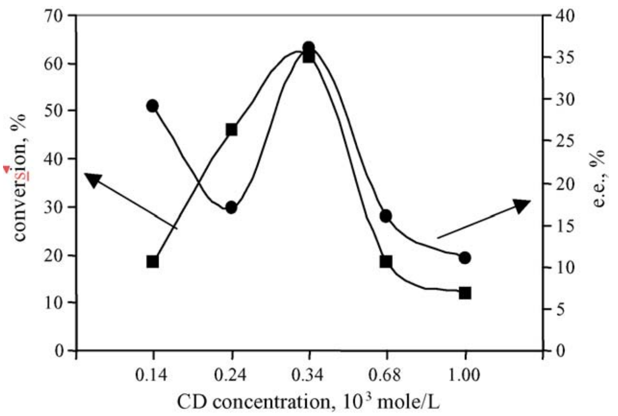

Fig. 7. Study of modifier concentration in the enantioselective hydrogenation of 1-phenyl-1,2-propanedione in cyclohexane over Ir/TiO_2 HT at 25 °C, 40 bar and 10^{-2} M of diketone concentration.

the dependence of the modifier concentration presents a bell-type curve during pyruvate hydrogenation. Similar results have been published by different authors [16–18].

Fig. 7 displays the change in the conversion level and in the enantiomeric excess as a function of modifier concentration. As expected a bell-type curve was observed not only for the e.e. but also for the conversion. In fact, when the catalyst (Ir/TiO_2 HT) was evaluated at a low CD concentration (2.4×10^{-4} M) and a higher diketone concentration (10^{-2} M), the activity and e.e. dropped significantly. These results indicate that the modifier not only induces chirality but also enhances the activity, which is in agreement with various authors [16,17,19].

At a lower CD concentration, only a slight fraction of the metallic phase is covered by the modifier and the remaining metal sites are occupied mainly by the substrate and dissociated hydrogen. The adsorbed modifier interacts with a diketone molecule forming an adsorbed supramolecule, which is hydrogenated by hydrogen spillover to produce the *R*-enantiomer. Additionally, the adsorbed substrate may also be hydrogenated, leading to the racemic mixture; therefore, on average, a low enantioselectivity may be achieved. Conversely, at a higher CD concentration, the formation of dimmers $(CD)_2$ is likely [15], limiting the amount of the desired enantiomer. Therefore, for each system, an optimum modifier concentration is required to reach high enantiomeric excess. The values compiled in Table 4 were obtained using the same CD concentration (3.4×10^{-4} M) was used in all experiments. Since the catalysts possess the loading but with different metal surface exposure, the CD concentration was not optimised for the studied system. Further improvements in the experimental conditions have been carried out allowing a significant increase in the reaction rate and enantioselectivity [20].

A similar explanation can be derived from the models proposed by various groups (Blaser, Baiker and Wells) working essentially with the hydrogenation of α-ketoester in the so-called "*The active chiral site model*". In this model, a chiral site is formed by the adsorption of a modifier molecule on the metal surface. There is no doubt that the chiral modification step is key in enabling the catalyst to behave enantioselectively. In this model, there is no requirement for the formation of an ordered arrangement of modifiers. Instead, the chiral-directing interaction was proposed to be between a single adsorbed modifier and a reactant molecule. If the chiral modifier is adsorbed parallel to the surface via its aromatic ring system, steric constraints imply that the N-atom of the quinuclidine moiety would be unable to interact with the surface and hence would be available to interact with the reactant molecule. It is proposed that during the hydrogenation reaction, the protonation of either the N-atom or the ketone O-atom results in the ability to form H-bonding interaction between the N-atom of the quinuclidine moiety and the ketone group of the reactant. If the geometry of the α-ketoester is sterically constrained in such a way that the intermediate to the *R*-product is favoured over the intermediate to the *S*-product, enantioselective hydrogenation would ensue. The stabilization of this partially hydrogenated intermediate by the modifier was also thought to have hydrogenated faster than an isolated α-ketoester molecule, and thus, accounting for the rate enhancement observed on chirally modified surfaces [21].

The second model, proposed by Margitfalvi et al. [22,23], *the shielding effect model*, suggests the formation of a weak complex between the modifier and the substrate in the liquid phase. In the above complex, the modifier provides a specific shielding effect (SE). Due to the particular character of shielding, the α-ketoester can interact with the metal surface only with its unshielded site. If the reactivity of the substrate in the shielded substrate–modifier complex is higher than that of the free substrate, significant enantiodifferentiation should be observed. In one of the shielded forms, the directionality characteristic of the quinuclidine nitrogen towards the carbonyl group provides the carbonyl group's increased reactivity. Even though calculations seem to be able to predict the preferred adsorption mode of the C=O bond, it is not clear which specific (repulsive) interactions are responsible for the discrimination. For the α-ketoethers, the favoured formation of the (*R*,*S*)-isomers was proposed to be due to the steric effect of the methyl group in the adsorbed state. However, the study of different interactions by others techniques such as, RMN [24], FTIR spectroscopy [25] and near-edge X-ray absorption fine structure (NEXAFS) [12,26,27] need to be carried out to develop the model of each specific system.

Whatever the model, the competition between the substrate and the modifier, or substrate and supramolecule to be adsorbed on the metal surface, may also be important to understand the obtained enantiomeric excess. Thus, if the modifier (or the supramolecule) is preferentially adsorbed, an important enantiomeric excess may be expected. Conversely, if the substrate is preferentially adsorbed, almost no chiral induction takes place and consequently, low e.e. should be obtained.

4. Conclusions

The hydrogenation of 1-phenyl-1,2-propanedione at 40 bar and 298 K was studied on different cinchona-modified Ir-supported catalysts. The obtained results indicate that catalysts in which the metal component Ir is present as an $Ir^{\delta+}$ species, the reaction rates increase as a consequence of the carbonyl bond polarisation. This species may be generated with the high temperature reduction, in the case of a partially reducible support, or by the addition of promoter oxides.

Since the catalysts studied in the present work exhibit comparable metal particle size, this effect, which is known to strongly influence enantioselectivity can be ruled out as an explanation of the observed differences in the different systems.

It was also found that the cinchonidine concentration significantly affects both activity and enatioselectivity, and therefore, the optimum modifier concentration should be used to improve the enantioselectivity towards the desired enantiomer for each system. Additionally, high regioselectivity values were obtained in all of the studied catalysts.

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