Available online at www.sciencedirect.com
SCIENCE DIRECT
Journal of Catalysis 241 (2006) 96–102
JOURNAL OF CATALYSIS
www.elsevier.com/locate/jcat

Origin of ligand acceleration in heterogeneous ethyl pyruvate hydrogenation

Esa Toukoniitty, Dmitry Yu. Murzin *

Laboratory of Industrial Chemistry, Process Chemistry Centre, Åbo Akademi University, Biskopsgatan 8, FIN-20500 Turku, Finland

Received 6 March 2006; revised 13 April 2006; accepted 13 April 2006

Available online 30 May 2006

Abstract

Ethyl pyruvate (EP) was hydrogenated in the presence and absence of cinchonidine (CD) over a broad concentration range of EP (0.01–2.0 mol L^{-1}) using a commercial 5% Pt/Al_2O_3 catalyst (Strem). Ligand acceleration (LA) could be observed at a higher concentration (0.3–2.0 mol L^{-1}), whereas at lower concentration, both enantioselective and racemic reactions have very similar reaction rates. Regardless of LA, a constant (84 ± 2%) enantiomeric excess (ee) could be obtained. As CD concentration was increased, the ee increased from 0 to 80%, while the hydrogenation rate remained constant at a low EP concentration (0.01 mol L^{-1}). Continuous fixed-bed reactor experiments revealed that LA can be linked to catalyst deactivation. In particular, EP causes catalyst deactivation, which is faster at higher reactant concentrations. CD restores catalyst activity and suppresses catalyst deactivation, resulting in higher reaction rates compared with racemic reactions carried out without CD.

Keywords: Heterogeneous catalysis; Hydrogenation; Enantioselectivity; Ligand acceleration

1. Introduction

Ethyl pyruvate (EP) hydrogenation over cinchonidine (CD)-modified Pt catalysts (Orito reaction) [1] is an actively investigated [2–14] example of ligand-accelerated heterogeneous catalysis [15,16], which yields >95% enantiomeric excess [17] (ee) and up to 100-fold higher reaction rate [18] in the presence of trace amounts of CD. Mechanistic models [14–23], which correctly predict the sense of chirality [i.e., (*R*)- or (*S*)-ethyl lactate (EL) enantiomer in excess], assume one-to-one reactant–modifier interactions, which result in notably increased reaction rate and ee. In light of the mechanistic models, however, the description of the effect of ligand acceleration (LA), also referred as rate acceleration, is far from quantitative, although the interrelationship of LA and ee on the modifier concentration is one feature on which most research groups working in the field have agreed. The mechanistic explanations of LA vary but are all related to the activation by CD on a modified catalytic site or in the supramolecular reactant–modifier complex in the shielding effect model [22]. Activation via EP–CD interactions results in LA and ee over modified sites, which are far less numerous than active hydrogenation sites during racemic hydrogenation due to significant CD coverage. Strongly adsorbing CD blocks a considerable fraction of the catalyst sites. Taking into account the 60–80% [24] loss of Pt surface area due to strong adsorption of CD, a 20- to 100-fold overall LA requires a 50–500 times higher TOF at the modified site, corresponding to a 10- to 15-kJ mol^{-1} difference in activation energy. To the best of our knowledge, to date no molecular-level feature [25] of CD–EP interaction has been successfully correlated with the very large LA effect, indicating also that the CD–EP interaction-based mechanism of LA is still largely without a sound theoretical basis. LA is clearly related to the presence of CD, and numerous studies have reported notably higher reaction rates for hydrogenation of EP in the presence of CD.

Recently, the origins of the LA were explained in a manner totally opposite to what the CD–EP interaction model assumes [26]. It was proposed that the higher reaction rate in the presence of CD is due to increased number of sites rather than to an increased turnover rate on a constant number of sites, as earlier models assumed. The mechanistic origin of LA was linked to more severe blocking of the catalyst surface by high-molecular mass products in the absence of CD. These activity–ee correlations were based on experiments with

* Corresponding author. Fax: +358 2 2154479.
E-mail address: dmurzin@abo.fi (D.Yu. Murzin).

0021-9517/$ – see front matter
doi:10.1016/j.jcat.2006.04.017

Bi- and S-poisoned catalysts. Increasing the Bi coverage at step sites increased activity substantially but reduced ee, whereas increasing the S adsorption at terrace sites decreased activity and increased ee. Despite the elegant demonstration that the ee and activity are not interrelated [26] the racemic hydrogenation in the absence of modifier was drastically slower than any of the reactions in the presence of catalyst modifier, thus exhibiting the LA phenomena.

Clearly, ee and activity are not directly interrelated in EP hydrogenation. This notion has recently received additional experimental support. EP hydrogenation using various silylated CD derivatives as catalyst modifiers was found to exhibit a lack of LA and relatively high ee (62–73%) [27]. Using α-isocinchonine and β-isocinchonine as catalyst modifiers resulted in moderate maximum ee values (20–34%), although the latter modifier exhibited LA, whereas the former did not [28]. Furthermore, von Arx et al. [29] reported that in gas-phase hydrogenation of methyl pyruvate, the presence of CD greatly reduced the reaction rate. In an earlier study, Margitfalvi et al. [30] also concluded, based on CD injection experiments in a batch reactor, that the rate acceleration and enantiodifferentiation might not have the same origin. The lack of LA in liquid-phase hydrogenation of a various other substrates is well documented [31].

In this work we report catalytic results supporting the concept that LA in EP hydrogenation has a different origin than previously assumed and can be linked to more severe EP-induced catalyst deactivation during racemic hydrogenation and to the ability of CD to slow this deactivation. Furthermore, we demonstrate that under reaction conditions that favor slower catalyst deactivation, the racemic and enantioselective reaction rates are very similar, and that the reaction rate is not proportional to the CD concentration, which have been the key mechanistic observations in previously developed kinetic models of EP hydrogenation.

2. Experimental

2.1. Catalysts and chemicals

Freshly vacuum-distilled EP (Fluka 15960, >97%) was hydrogenated in a pressurized batch reactor (Parr, $V_L = 100$ cm^3) over 5 wt% Pt/Al_2O_3 catalyst (Strem, 78-1660, BET specific surface area 95 m^2 g^{-1}; mean Pt particle size, 8.3 nm [X-ray diffraction], dispersion, 40% [H_2 chemisorption]; mean catalyst particle size, 18.2 μm [Malvern]) at 10 bar hydrogen (AGA, 99.999%) pressure and 15 °C [32]. Details on the 5 wt% Pt/SiO_2 (Fibre) catalyst preparation and characterization have been given previously [33]. Toluene (Baker, >99.5%), quinuclidine (Fluka 22709, >97%), and CD (Fluka 27350, >98%) were used as received.

2.2. Hydrogenation experiments

2.2.1. Hydrogenation in a batch reactor

The catalyst mass and liquid volumes were 50 mg (except in the experiments with 4.5, 12.5, and 25 mg) and 100 cm^3, respectively, and the stirring speed was 2000 rpm. The catalyst was activated under hydrogen flow (50 cm^3 min^{-1}) for 2 h at 400 °C. The preactivated catalyst and solvent (50 cm^3) containing dissolved CD (typically 10 mg) were loaded into the reactor and flushed with hydrogen for 10 min at 1 bar. During this time, the vinyl group of CD partially hydrogenated to give 10,11-dihydrocinchonidine (HCD). CD and HCD are known to be similar in terms of kinetic behavior and to result in nearly the same reaction rate and ee [34]. Furthermore, during the first minutes of the actual hydrogenation (at 15 °C and 10 bar H_2), CD is hydrogenated to HCD, making it the actual modifier during the main course of the reaction. Transformation of the modifier by hydrogenation of the adsorbing quinoline ring takes much longer [35] and results in drastically reduced ee and reaction rates [3]. Because the ee does not decrease with reaction time, the transformation of the quinoline ring can be safely assumed to have a negligible influence on the kinetics under our reaction conditions. The reactant solution (50 cm^3) was saturated with hydrogen for 10 min in a separate injection chamber and injected into the reactor, immediately after which the reaction was started by initiating agitation. Contact of EP and catalyst could be avoided before starting the hydrogenation by using the reactant injection procedure, whereas CD, catalyst, and solvent were in contact with one another for about 10 min before hydrogenation. Racemic reactions were carried out using the same experimental procedure, but using no CD. Once the reaction started, the pressure and temperature were constant ($p = \pm 0.1$ bar; $t = \pm 0.5$ °C) within <1 min of reaction.

A note on reproducibility and experimental error: The experiments were carried out using the same batch of catalyst and EP, and the experimental error in the initial reaction rates and ee's were <10% of the reported values based on reproducibility experiments. In this work when referring to rate, we are using initial rates calculated from the slope at $t = 0$ of hydrogen uptake versus the time curve.

2.2.2. Hydrogenation in a fixed-bed reactor

The experiments in continuous fixed-bed reactor were carried out using the same conditions (H_2 pressure, temperature, and solvent) and catalyst as in the batch reactor experiments. The experimental conditions are outlined in the figure captions. Additional details of the continuous reactor setup and procedures have been reported previously [36].

3. Results

3.1. Effect of EP concentration

The hydrogenations were carried out over a commercial 5 wt% Pt/Al_2O_3 catalyst in a batch reactor under kinetic control. EP concentration was varied between 0.01 and 2.0 mol L^{-1} in racemic and enantioselective reactions in the presence of CD (Fig. 1) at 15 °C and 10 bar H_2 pressure in toluene. The highest racemic reaction rate was observed at 0.1 mol L^{-1} c_0(EP), resulting in a TOF of 3400 h^{-1} (57 mmol L^{-1} min^{-1} g^{-1}). The highest enantioselective reaction rate was observed at the highest c_0(EP) used, giving a TOF of 12,000 h^{-1} (200 mmol L^{-1}

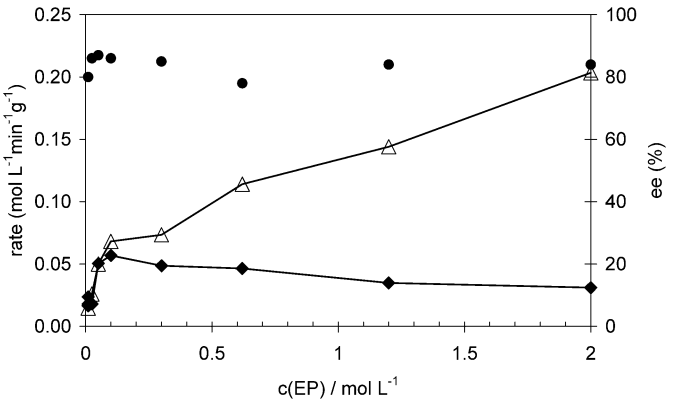

Fig. 1. Initial hydrogenation rates of enantioselective (△) and racemic hydrogenation (◆) and the enantiomeric excess (●). Conditions: $c_0(\mathrm{CD}) = 3.4 \times 10^{-4}$ mol L^{-1} (only in enantioselective reactions), 50 mg 5 wt% Pt/Al_2O catalyst, toluene, 15 °C, 10 bar H_2.

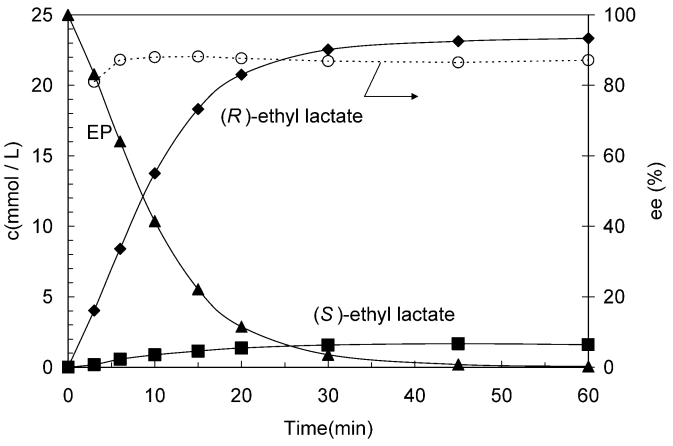

Fig. 2. Typical kinetics. Symbols (▲) EP, (◆) (*R*)-ethyl lactate, (■) (*S*)-ethyl lactate, (○) enantiomeric excess, ee. Conditions: $c_0(\mathrm{EP}) = 0.025$ mol L^{-1}, $c_0(\mathrm{CD}) = 3.4 \times 10^{-4}$ mol L^{-1}, 50 mg 5 wt% Pt/Al_2O catalyst, toluene, 15 °C, 10 bar H_2.

min^{-1} g^{-1}) and a six-fold LA, which decreased with decreasing c_0(EP). The racemic reaction rate exhibited a maximum at relatively low reactant concentrations, whereas in enantioselective reaction the rate increased with increasing reactant concentration.

At low EP concentration (<0.1 mol L^{-1}), LA disappeared, and both enantioselective and racemic reactions proceeded at similar rates (Fig. 1). All of the low-concentration experiments ($c_{\mathrm{EP}} < 0.3$ mol L^{-1}) were repeated 2–4 times, and experimental error in the initial rates can be excluded as a reason for the observed lack of LA. The lack of LA at low c_0(EP) was also observed over 5% Pt/SiO_2(fiber) catalyst (not shown), indicating that this effect is not specific to the 5% Pt/Al_2O_3 catalyst. Regardless of the LA, in all enantioselective reactions the 84 ± 2% final ee of (*R*)-ethyl lactate (EL) was observed independent of EP concentration (calculated based on 14 experiments at a 95% confidence level).

The initial transient period, often reported in EP hydrogenation [37], was observed in ee; that is, the initial ee at low conversion was often 10–20% lower that the final product ee (see Fig. 2). The initial transient period reduced the ee in the first and maximum second data point(s) only; therefore, the effect of this on the reported initial reaction rates can be considered negligible, because the rates were typically calculated from first four data points. Furthermore, there is a convincing inverse correlation between initial reaction rate and the time needed to reach full conversion. Therefore, comparing initial rates and the final product ee (which can be more accurately determined from experimental data than, say, initial ee and time to 100% conversion) is justified, with no risk of arriving at false mechanistic conclusions.

An analysis of general kinetic regularities for both racemic and enantioselective reactions at various reactant concentrations indicated that in all cases the concentration versus time plots were similar. The maximum rate in racemic hydrogenation (Fig. 1) at 0.1 mol L^{-1} cannot be explained by, say, notable changes in kinetic regularities, for example, changes in reaction order with respect to the reactant during hydrogenation experiments (see supporting material for additional details).

The individual formation rates of (*R*)-EL and (*S*)-EL for the set of experiments displayed in Fig. 1 reveal interesting mechanistic details. Using the formation rate of (*R*)-EL or (*S*)-EL during a racemic reaction as a reference point, it can be noted that the enantioselective formation rates of both (*R*)-EL and (*S*)-EL can be higher (2.0 mol L^{-1}), the rate of (*R*)-EL can be higher and that of (*S*)-EL equal (1.2 mol L^{-1}), the rate of (*R*)-EL can be higher and that of (*S*)-EL lower (0.05–0.62 mol L^{-1}), or the rates of both (*R*)-EL and (*S*)-EL can be lower (0.01 mol L^{-1}) with respect to racemic hydrogenation. Therefore, the difference in formation rates of (*R*)-EL and (*S*)-EL define ee and has no explicit connection to the racemic rate.

A literature survey reveals that most of the experimental data reported in the literature on EP hydrogenation was obtained at rather high c_0(EP), explaining why the absence of LA at low EP concentrations went unnoticed. However, a few publications have reported a lack of LA at low reactant concentration in liquid-phase hydrogenation of EP [27,31] and in gas-phase hydrogenation of methyl pyruvate [29].

3.2. Effect of CD concentration

One of the key kinetic observations leading to the development of the LA concept in EP hydrogenation was the dependence of ee and reaction rate on the modifier concentration. Typically, the ee and reaction rate increase with increasing modifier concentration, reaching a plateau or a broad maximum at high modifier concentrations. In the present work, as concentration of CD was varied at low $c_0(\mathrm{EP}) = 0.01$ mol L^{-1}, the ee varied between 0 and 80% and was proportional to the amount of CD present. However, the reaction rates remained the same (Fig. 3), demonstrating no dependence on the amount of CD typically observed at higher c_0(EP). These experimental observations cannot be rationalized in the framework of mechanisms that assume increased turnover rates on modifier sites [19,22,38], and they do not support the commonly accepted interrelationship of reaction rate, modifier concentration, and ee.

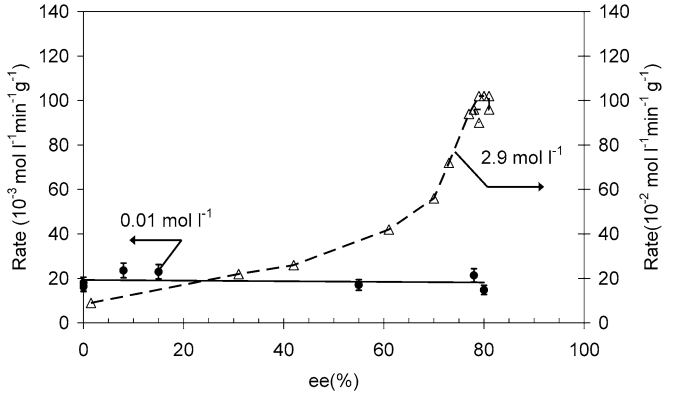

Fig. 3. Enantiomeric excess (ee) vs. initial hydrogenation rate at high and low initial EP concentrations. Symbols: (—) c_0(EP) = 0.01 mol L^{-1} (data from current work, experiments carried out at different CD concentrations 0, 4 × 10^{-7}, 1 × 10^{-6}, 3.4 × 10^{-6}, 3.4 × 10^{-5} and 3.4 × 10^{-4} mol L^{-1}), 50 mg 5 wt% Pt/Al_2O catalyst, toluene, 15 °C, 10 bar H_2. (- - -) c_0(EP) = 2.9 mol L^{-1} (Data taken from [47], conditions: toluene, 20 °C, 20 bar H_2).

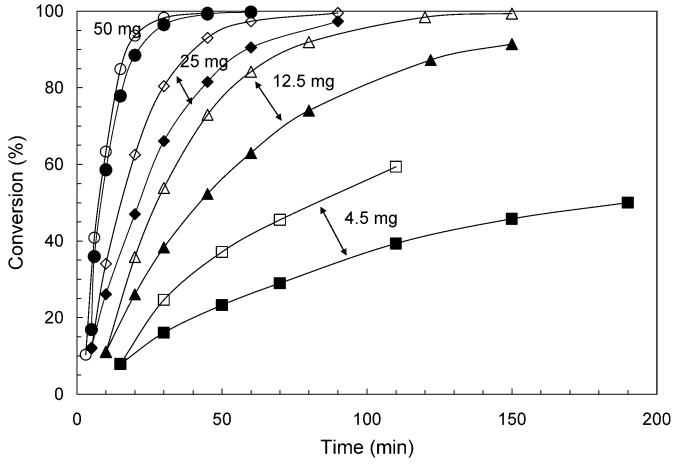

Fig. 4. Effect of EP-to-catalyst ratio. Open symbols: racemic reaction, full symbols: enantioselective reaction. Conditions: c_0(EP) = 0.025 mol L^{-1}, c_0(CD) = 3.4 × 10^{-4} mol L^{-1} (only in enantioselective reactions), toluene, 15 °C, 10 bar H_2.

3.3. Effect of catalyst amount

In this work, the molar ratio n(EP)-to-n($Pt_{surface}$) varied from 200 (0.01 mol L^{-1}) to 40,000 (2.0 mol L^{-1}). It is clear that at higher c_0(EP), LA appears (Fig. 1); however, at the same time also the EP-to-catalyst ratio changes, which might contribute to the observed LA effect. To test whether LA could be observed at higher EP-to-catalyst ratio also at c_0(EP) = 0.025 mol L^{-1}, both racemic and enantioselective reaction were carried out using different amounts of catalyst (Fig. 4). The lowest amount of catalyst corresponds to the same EP-to-catalyst ratio used at c_0(EP) = 0.3 mol L^{-1} (Fig. 1), where the enantioselective reaction had a 1.5-fold higher reaction rate. However, the 1.5-fold rate acceleration observed at c_0(EP) = 0.3 mol L^{-1} was not observed at the same EP-to-catalyst ratio at c_0(EP) = 0.025 mol L^{-1}.

In contrast, the racemic reactions were slightly faster than the enantioselective reactions, indicating that LA cannot be correlated with the EP-to-catalyst ratio. Interestingly, as the catalyst amount was decreased, the difference between the racemic and enantioselective reaction rates increased, with the former being faster. In fact, instead of LA, the catalyst modifier caused ligand deceleration (LD). Assuming that little catalyst deactivation occurred due to low c_0(EP), the strongly adsorbing CD would block some fraction of the surface, making the enantioselective reactions actually slower than the racemic reactions. In these experiments (Fig. 4), the concentration of CD was kept constant, meaning that as the catalyst amount was decreased from 50 to 4.5 mg, the CD-to-catalyst mass ratio increased from 0.2 to 2.2, which would account for the further reduced rate of the enantioselective reactions compared with the racemic reactions.

3.4. Effect of quinuclidine

Previous observations on the effect of quinuclidine have demonstrated that quinuclidine induces notable LA in pyruvate hydrogenation [26,39,40] and increases ee under certain experimental conditions. In the racemic hydrogenation of methyl pyruvate, quinuclidine induced a 6.5-fold rate acceleration [40]. In the presence of CD during enantioselective hydrogenation of EP, quinuclidine increased the reaction rate and the ee by up to 94% [39]; however, this beneficial effect was limited to low modifier concentrations ($c_M < 10^{-4}$ mol L^{-1}). Alternatively, quinuclidine has been reported to significantly increase the rate and only slightly influence ee [26] using relatively high concentrations of CD and quinuclidine (9 mmol L^{-1}). In the latter case, the beneficial effect was explained by quinuclidine's ability to suppress catalyst deactivation. All of these experiments were carried out at relatively high reactant concentrations ($\leqslant$1.0 mol L^{-1}), and it is interesting to see whether quinuclidine would induce a positive effect under the experimental conditions used in this work.

The reaction was carried out by modifying with quinuclidine and quinuclidine + CD using a molar equivalent of the amount of CD [c_0(CD) and c_0(quinuclidine), both 3.4 × 10^{-4} mol L^{-1}] at c_0(EP) = 0.025 mol L^{-1}. In the presence of CD + quinuclidine, the reaction rate decreased by 20% compared with the absence of quinuclidine and the ee dropped slightly, from 87 to 80%. The effect of quinuclidine during racemic reactions was more pronounced; the reaction rate dropped by 50%, while the obtained ee remained at 0%, as would be expected. Therefore, the previously reported beneficial effects of quinuclidine at higher c_0(EP) on reaction rate and ee were not obtained at low c_0(EP). In fact, quinuclidine had a slight negative effect on the ee and a pronounced negative effect on the reaction rate. This can be understood keeping in mind that quinuclidine has been assumed to prevent catalyst deactivation. In the absence of catalyst deactivation, no dramatic rate enhancement from adding quinuclidine can be observed. Quinuclidine can be expected to adsorb on Pt, which can cause the reduced reaction rate. This is in accordance with the hypothesis that the absence of LA at low c_0(EP) is due to negligible catalyst deactivation.

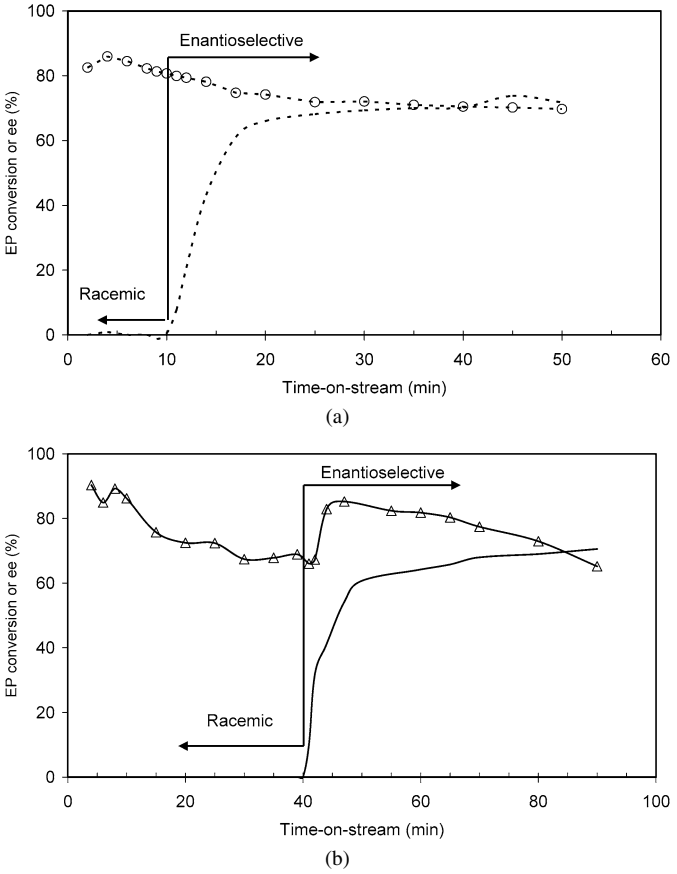

Fig. 5. EP hydrogenation in a continuous fixed bed reactor. (a) CD introduced in the inlet feed at 10 min time-on-stream, (b) CD introduced in the inlet feed at 40 min time-on-stream. Conditions: c_0(EP) = 0.01 mol L^{-1}, c_0(CD) = 3.4 × 10^{-4} mol L^{-1}, liquid flow rate 3.50 cm^3 min^{-1}, H_2 flow rate 50 cm^3 min^{-1}, 15 °C, 10 bar H_2, solvent toluene, 25 mg of 5 wt% Pt/Al_2O_3 catalyst. Symbols: (line) enantiomeric excess, (line + symbols) conversion of EP.

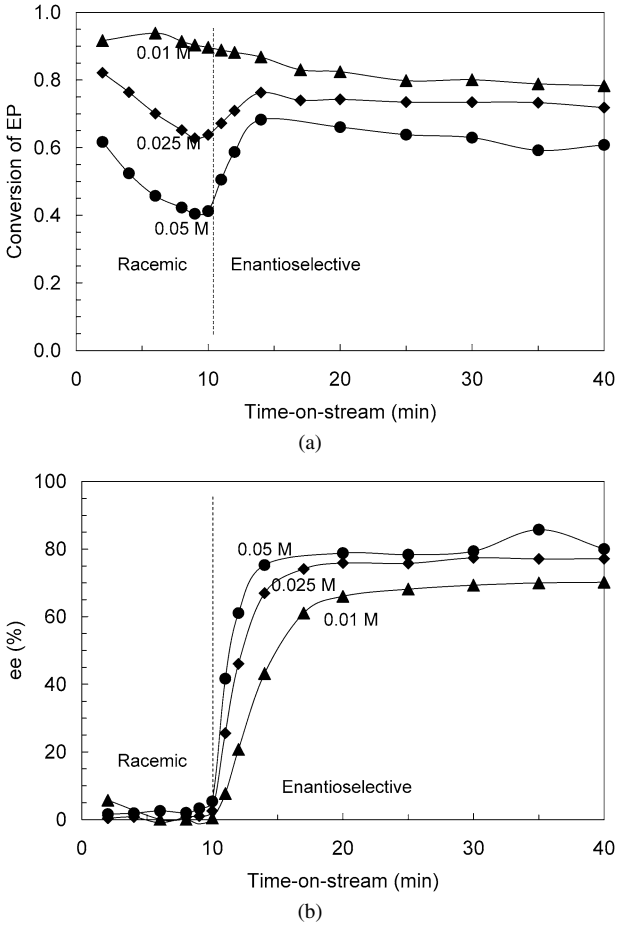

Fig. 6. EP hydrogenation in a continuous fixed bed reactor. (a) EP conversion, (b) enantiomeric excess of (*R*)-EL. CD introduced in the inlet feed at 10 min time-on-stream. Conditions: c_0(CD) = 3.4 × 10^{-4} mol L^{-1}, liquid flow rate 3.50 cm^3 min^{-1}, H_2 flow rate 50 cm^3 min^{-1}, 15 °C, 10 bar H_2, solvent toluene, 25 mg of 5 wt% Pt/Al_2O_3 catalyst.

3.5. Continuous reactor experiments

During EP hydrogenation in a continuous fixed-bed reactor, a connection between LA and deactivation was established (Fig. 5). CD induced ee in a continuous reactor at a level almost comparable to the ee obtained in a batch reactor (70–80%). It has been reported that under continuous operation, the optimum modifier concentration is higher than that in batch reactor experiments, which explains the slightly lower ee [41]. LA was observed on introduction of CD only if the catalyst was deactivated, that is, when the activity was well below the initial activity. But obtaining notable deactivation at low EP concentration [c_0(EP) = 0.01 mol L^{-1}] required a 40-min time on stream of racemic reaction. In a batch reactor at the same EP concentration, total conversion was achieved already after 20 min. Therefore, at low initial EP concentration, the hydrogenation reaction can reach full conversion before notable catalyst deactivation occurs.

Transient experiments in the fixed-bed reactor at various inlet concentrations of EP (0.01, 0.025, and 0.05 mol L^{-1}) demonstrated faster deactivation at higher EP concentration in the absence of modifier (the first 10 min in Fig. 6a). Furthermore, introduction of CD in the inlet feed after 10 min time on stream increased reaction rate close to the initial level (Fig. 6a). After introduction of CD in the inlet feed also the deactivation rate seems to slow down. A higher inlet concentration of EP is beneficial for higher steady-state ee and is also attained faster (Fig. 6b).

Based on the results of our transient fixed-bed reactor experiments, it can be concluded that CD-induced LA could also be observed at low c_0(EP) provided that the catalyst had been deactivated noticeably. CD evidently can regenerate the already-deactivated catalyst activity close to the initial level and suppress the deactivation rate, which is higher at higher inlet concentrations of EP (Fig. 6a).

4. Discussion

We have shown for the first time that EP can be hydrogenated with high ee (84%) without LA over CD-modified Pt/Al_2O_3 catalyst. The experimental data obtained at low c_0(EP) demonstrates that reaction rate and c_0(CD) do not correlate, whereas c_0(CD) and ee do correlate. The experimental observations are in line with a previous proposition [26] that the origin of the LA effect in heterogeneous EP hydrogenation lies in CD's ability to prevent side reactions, which deactivate the catalyst, rather than

in EP–CD interactions, as is often conjectured. The connection of catalyst deactivation and LA observed in continuous fixed-bed reactor, as well as CD's ability to prevent and restore the catalyst activity, lend further support to this mechanistic view of LA. Furthermore, it is interesting to note (keeping in mind the catalyst deactivation aspect) that the reported LA values vary greatly even though similar ee values are reported. The slightly varying experimental procedures and contact order of solvent, modifier, EP, hydrogen, and catalyst can significantly influence catalyst deactivation.

Based only on kinetic experiments, the actual deactivation reactions, which reduce the activity of the racemic reaction and contribute to the LA effect, cannot be determined. However, several possibilities have been discussed in the literature [26,31, 42–46]. Methyl pyruvate undergoes aldol-type polymerization on Pt in the absence of CD and H_2 under UHV conditions, also producing CO [42]. Gas-phase FTIR measurements have shown that EP decomposes over a Pt/Al_2O_3 catalyst, producing CO and strongly adsorbed $C_XH_YO_Z$ species [37]. A recent ATR-IR study provided two important observations regarding EP decomposition over Pt: (1) EP decomposition proceeded 60 faster in the absence of CD, and (2) at low $c(\mathrm{EP}) = 0.001\ \mathrm{mol\,L^{-1}}$, the decomposition reaction was relatively slow, on the order of several minutes [45]. It would be interesting to compare which of these side reactions might be operative under our experimental conditions. Unfortunately, little is known about the kinetics of these side reactions; it may be that several of these reactions are operative under typical reaction conditions, all contributing to more severe catalyst deactivation in the absence of CD.

It is interesting to note that several substrates have been hydrogenated over CD-modified catalyst with only modest or no LA [31], supporting the conclusion that LA is not needed for high ee. The LA also depends on the catalytic metal; for example, EP hydrogenation over Pd catalyst does not exhibit LA [48]. As far as we know, decomposition studies in the presence and absence of CD have not been carried out with substrates other than methyl pyruvate and EP. Studying the aforementioned deactivation reactions with other substrates and attempting to find correlations between the LA effect and catalyst deactivation could help identify the prevailing deactivation reactions.

The dual role of CD as a promoter (side reaction inhibitor) and a chiral poison (strong adsorption on Pt with high coverage) provides a feasible explanation for the kinetic results reported here and is in line with the pertinent kinetic regularities of EP hydrogenation. Furthermore, it provides a plausible mechanistic connection between well-documented LA results at high c_0(EP) and experimental data reporting LD at low c_0(EP). Therefore, the origin of LA can be linked to CD's ability to prevent EP-induced catalyst deactivation during enantioselective hydrogenation.

5. Conclusion

By accounting for catalyst deactivation, a kinetic explanation for both low- and high- concentration domains of EP hydrogenation can be posited that allows equal ee independent of EP concentration and also provides a plausible mechanistic explanation of the roles of CD and nonchiral additive compounds (e.g., quinuclidine) in LA processes. In EP hydrogenation, CD acts as a chiral-directing agent, enabling enantioselectivity, and as a side reaction inhibitor. The enantiodifferentiating interactions that induce ee occur between EP and CD, whereas the LA originates from CD's ability to hinder side reactions, leading to EP decomposition and catalyst deactivation. The experimental data suggest that kinetic and mechanistic models for enantioselective EP hydrogenation should account for this explanation of the origin of LA.

Acknowledgments

This work is part of the activities at the Åbo Akademi Process Chemistry Centre within the Finnish Centre of Excellence Programme (2006–2011) by the Academy of Finland. Financial support from the Academy of Finland (project 204724) is gratefully acknowledged by E.T.

Supporting information

The online version of this article contains additional supplementary material: Concentration versus time data for the experiments presented in Fig. 1.

Please visit DOI:10.1016/j.jcat.2006.14.017.

References

[1] Y. Orito, S. Imai, S. Niwa, J. Chem. Soc. Jpn. 8 (1979) 1118.
[2] C. Exner, A. Pfaltz, M. Studer, H.-U. Blaser, Adv. Synth. Catal. 345 (2003) 1253.
[3] H.-U. Blaser, H.P. Jalett, W. Lottenbach, M. Studer, J. Am. Chem. Soc. 122 (2000) 12675.
[4] T. Bürgi, A. Baiker, Acc. Chem. Res. 37 (2004) 909.
[5] M. Studer, H.-U. Blaser, C. Exner, Adv. Synth. Catal. 345 (2003) 45.
[6] P.B. Wells, R.P.K. Wells, in: D.E. Vos, I.F.J. Vankelecom, P.A. Jacobs (Eds.), Chiral Catalyst Immobilization and Recycling, Wiley–VCH, Weinheim, 2000, pp. 123–154.
[7] M. Bartók, M. Sutyinszki, I. Bucsi, K. Felföldi, G. Szöllősi, F. Bartha, T. Bartók, J. Catal. 231 (2005) 33.
[8] X. Li, R.P.K. Wells, P.B. Wells, G.J. Hutchings, J. Catal. 221 (2004) 653.
[9] C. LeBlond, J. Wang, J. Liu, A.T. Andrews, Y.-K. Sun, J. Am. Chem. Soc. 121 (1999) 4920.
[10] A. Pfaltz, T. Heinz, Top. Catal. 4 (1997) 229.
[11] X. Zuo, H. Liu, D. Guo, X. Yang, Tetrahedron 55 (1999) 7787.
[12] M. Bartók, P.T. Szabó, T. Bartók, G. Szöllösi, Rapid Commun. Mass Spectrom. 14 (2000) 509.
[13] X. Li, R.P.K. Wells, P.B. Wells, G.J. Hutchings, J. Catal. 221 (2004) 653.
[14] K. Balázsik, M. Bartók, J. Catal. 224 (2004) 463.
[15] D.J. Berrisford, C. Bolm, K.B. Sharpless, Angew. Chem. Int. Ed. 34 (1995) 1059.
[16] M. Garland, H.-U. Blaser, J. Am. Chem. Soc. 112 (1990) 7048.
[17] B. Török, K. Balázsik, G. Szöllösi, K. Felföldi, M. Bartók, Chirality 11 (1999) 470.
[18] H.-U. Blaser, H.P. Jalett, D. Monti, J.F. Reber, J.T. Wehrli, Stud. Surf. Sci. Catal. 41 (1988) 153.
[19] G. Vayner, K.N. Houk, Y.-K. Sun, J. Am. Chem. Soc. 126 (2004) 199.
[20] T. Bürgi, A. Baiker, J. Catal. 194 (2000) 445.
[21] K.E. Simons, P.A. Meheux, S.P. Griffiths, I.M. Sutherland, P. Johnston, P.B. Wells, A.F. Carley, M.K. Rajumon, M.W. Roberts, A. Ibbotson, Rec. Trav. Chim. Pays-Bas 113 (1994) 365.

[22] J.L. Margitfalvi, E. Talas, E. Tfist, C.V. Kumar, A. Gergely, Appl. Catal. A 191 (2000) 177.
[23] R.L. Augustine, S.K. Taneilyan, L.K. Doyle, Tetrahedron: Asymmetry 4 (1993) 1803.
[24] G.A. Attard, J. Phys. Chem. B 105 (2001) 3158.
[25] A. Vargas, T. Bürgi, M. von Arx, R. Hess, A. Baiker, J. Catal. 209 (2002) 489.
[26] D.J. Jenkins, A.M.S. Alabdulrahman, G.A. Attard, K.G. Griffin, P. Johnston, P.B. Wells, J. Catal. 234 (2005) 230.
[27] I. Busygin, E. Toukoniitty, R. Sillanpää, D.Yu. Murzin, R. Leino, Eur. J. Org. Chem. 13 (2005) 2811.
[28] J.L. Margitfalvi, E. Tálas, Appl. Catal. A: Gen. 301 (2006) 187.
[29] M. von Arx, N. Dummer, D.J. Willock, S.H. Taylor, R.P.K. Wells, P.B. Wells, G.J. Hutchings, Chem. Commun. (2003) 1926.
[30] J.L. Margitfalvi, B. Minder, E. Talas, L. Botz, A. Baiker, in: L. Guzi, et al. (Eds.), Stud. Surf. Sci. Catal., vol. 75, Elsevier Science Publishers, Amsterdam, 1993, p. 2471.
[31] D.Yu. Murzin, P. Mäki-Arvela, E. Toukoniitty, T. Salmi, Catal. Rev.-Sci. Eng. 47 (2005) 175.
[32] E. Toukoniitty, P. Mäki-Arvela, A. Nunes Villela, A. Kalantar Neyestanaki, R. Leino, T. Salmi, R. Sjöholm, E. Laine, J. Väyrynen, T. Ollonqvist, P. Kooyman, Catal. Today 60 (2000) 175.
[33] E. Toukoniitty, P. Mäki-Arvela, A. Kalantar Neyestanaki, T. Salmi, D.Yu. Murzin, Appl. Catal. A: Gen. 235 (2002) 125.
[34] H.U. Blaser, H.P. Jalett, D.M. Monti, A. Baiker, J.T. Wehrli, Stud. Surf. Sci. Catal. 67 (1991) 147.
[35] V. Morawsky, U. Prüße, L. Witte, K.-D. Vorlop, Catal. Commun. 1 (2000) 15.
[36] E. Toukoniitty, D.Yu. Murzin, Catal. Lett. 93 (2004) 171.
[37] T. Mallat, Z. Bodnar, B. Minder, K. Borszeky, A. Baiker, J. Catal. 168 (1997) 183.
[38] H.-U. Blaser, H.-P. Jalett, M. Garland, M. Studer, H. Thies, A. Wirth-Tijani, J. Catal. 173 (1998) 282.
[39] J.L. Margitfalvi, E. Talas, M. Hegedus, Chem. Commun. (1999) 645.
[40] G. Bond, P. Meheux, A. Ibbotson, P.B. Wells, Catal. Today 10 (1991) 371.
[41] N. Künzle, R. Hess, T. Mallat, A. Baiker, J. Catal. 186 (1999) 239.
[42] J.M. Bonello, F.J. Williams, A.K. Santra, R.M. Lambert, J. Phys. Chem. B 104 (2000) 9696.
[43] M. Bonello, R.M. Lambert, N. Künzle, A. Baiker, J. Am. Chem. Soc. 122 (2000) 9864.
[44] M. von Arx, T. Mallat, A. Baiker, Top. Catal. 19 (2002) 75.
[45] D. Ferri, T. Bürgi, A. Baiker, J. Phys. Chem. B 108 (2004) 14384.
[46] D. Ferri, S. Diezi, M. Maciejewski, A. Baiker, Appl. Catal. A: Gen. 297 (2006) 165.
[47] H.-U. Blaser, M. Garland, H.P. Jalett, J. Catal. 144 (1993) 569.
[48] P.J. Collier, T.J. Hall, J.A. Iggo, P. Johnston, J.A. Slipszenko, P.B. Wells, R. Whyman, Chem. Commun. (1988) 1451.