Catal Lett (2008) 125:401–407
DOI 10.1007/s10562-008-9576-4

New Data on the Orito Reaction: Effect of Substrate Structure on Nonlinear Phenomenon

Katalin Balázsik · Szabolcs Cserényi · György Szöllősi · Ferenc Fülöp · Mihály Bartók

Received: 14 May 2008 / Accepted: 4 July 2008 / Published online: 23 July 2008

Abstract The nonlinear phenomenon (NLP) was studied for the first time in the enantioselective hydrogenation of ethyl pyruvate (EP) and ketopantolactone (KPL) under identical conditions, on Pt catalyst modified by quinine and cinchonine, and for comparison with cinchonidine-cinchonine pair. The data obtained using the three methods allowed recognition of a new observation, namely that the NLP depends not only on the chiral modifier but also on the substrate to be hydrogenated. This observation can presumably be interpreted on the basis of differences in the structure of the substrate-modifier complexes formed and in the adsorption-desorption processes of the complexes, thus the NLP is not solely dependent on the adsorption of cinchona alkaloids, as suggested by earlier experimental data.

Keywords Asymmetric hydrogenation · Platinum · Cinchona alkaloids · Nonlinear phenomenon · Ketopantolactone · Ethyl pyruvate

1 Introduction

The most important research task in heterogeneous catalytic reactions is the best possible knowledge of the reaction mechanisms. New phenomena observed in the course of manifold investigations raise new problems, which call for further investigations and solutions. All this is especially true for the two most intensively studied enantioselective heterogeneous catalytic hydrogenations, namely the hydrogenations of prochiral ketones and of compounds containing prochiral C = C bonds on modified Ni [1] and on modified Pt and Pd catalysts (Orito reaction, Scheme 1) [2]. The complexity of the latter reaction and the achievement of enantioselectivity over 90% [3–5] have already necessitated wide-range complex investigations (see e.g. the reviews published since 2005 [6, 7]). Part of these is the study of the so-called nonlinear phenomenon (NLP), which has attracted the interest of specialists studying not only organic catalysis [8] but also other areas [9].

The "nonlinear effect" may arise in the interaction of a substrate with two enantiomers of opposite configurations and was first recognized in 1986, in a study on homogeneous asymmetric catalysis. Nonlinearity in the Orito reaction was first observed by Wells et al. in the hydrogenation of methyl pyruvate (MP) [8a, b]. Baiker et al. and later many other authors have widely utilized NLP in their studies on the heterogeneous enantioselective hydrogenation of activated ketones [7d, 8d, 10]. The results of studies carried out to date (using modifier mixtures, transient method in batch reactor, continuous flow measurements) can be summarized as in a very recently published review: "An essential conclusion from this study is that, although strong adsorption is a crucial requirement for an efficient modifier, there is no positive correlation between the adsorption strength (AS) and the enantioselectivity achieved with the modifier alone" [7d].

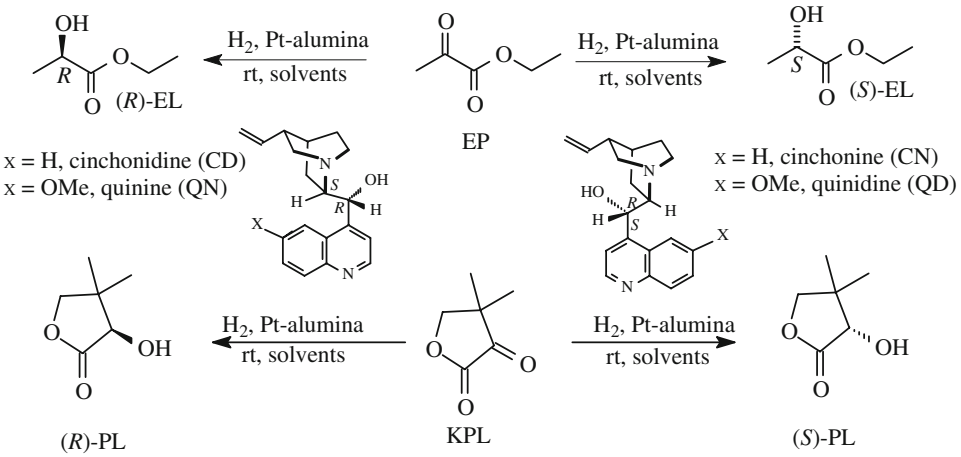
Experimental results on NLP have yielded, on one hand, information on the AS and the way of adsorption of chiral

K. Balázsik · S. Cserényi · G. Szöllősi · F. Fülöp · M. Bartók
Stereochemistry Research Group of the Hungarian Academy of Sciences, Dóm tér 8, 6720 Szeged, Hungary

F. Fülöp
Institute of Pharmaceutical Chemistry, University of Szeged, Eötvös u 6, 6720 Szeged, Hungary

M. Bartók (✉)
Department of Organic Chemistry, University of Szeged, Dóm tér 8, 6720 Szeged, Hungary
e-mail: bartok@chem.u-szeged.hu

Scheme 1



modifiers. On the other hand, studies on NLP have also contributed with new experimental evidence to the elucidation of the mechanism of the Orito reaction, namely they have verified that, in the hydrogenation of ethyl pyruvate (EP) and ketopantolactone (KPL), the intermediate complex (IC) responsible for chiral induction is the 1:1 complex of the chiral modifier and the substrate formed on the catalyst surface [7d, 8d, 10].

One of the debated questions in the NLP research is the order of the AS of cinchona alkaloids serving as modifiers of the Pt catalyst in the Orito reaction [8, 9]. The authors of the present report also encountered this problem [10], which made further research necessary, namely the investigation of factors affecting the adsorption of the parent cinchona alkaloids (CD, CN, QN, QD) on Pt. The NLP measurements in the Orito reaction to date have established the order CD > CN > QN > QD for the AS of cinchona alkaloids [8, 10], whereas RAIRS measurements yielded a significantly different order [9a]: QN, QD > CD > CN. The observations differing from the previous reports were commented by Ma and Zaera as follows:

"Interestingly, the higher AS of QD relative to CD reported here *contradicts* previous reports[4,21] ….. More work is needed to settle this *controversy*…" [9a]. Baiker and coworkers reflected to this: "Interestingly, Ma and Zaera [50] found the opposite order of AS based on RAIRS measurements in CCl_4, but at unusually high alkaloid concentrations.", and based on their own experimental results concluded: "These values confirm that CD is far more effective than QD and that the influence of alkaloid concentration is minor" [17].

Based on the results of more recent RAIRS experiments on this topic [9b], and in view of the results published by the Baiker group presented in ref. [17], Zaera and coworkers draw the conclusions: "These observations raise interesting questions regarding the factors that control relative adsorption strengths among seemingly similar molecules. The adsorption equilibrium constants (K_{ads}) were found to follow the sequence CN > QD > CD > QN. Perhaps a more surprising result from this work is the fact that CN displays a higher K_{ads} than CD, QN, or QD even through, according to previous work, it can be easily displaced from the surface by any of those other cinchona alkaloids. A full explanation of these observations requires consideration of the solvent above the adsorbed species" [9b].

In any case it may be established that on the one hand there are debated questions (different relative AS order) and on the other hand the very recent reports used the term "relative adsorption strength" in connection with the NLP investigations. In order to verify this contradiction, we used all three methods previously applied in NLP studies to investigate the enantioselective hydrogenation of EP and KPL in two solvents (toluene, AcOH) under fully identical experimental conditions. The three methods are: mixtures of two modifiers in batch reactor, transient method in batch reactor and transient method in a continuous-flow system using fixed-bed reactor (CFBR).

The experimental data obtained by using the CN-QN cinchona pair shown in the following were indicative of a novel observation in NLP. These observations may be considered indirect evidence for the mechanistic models assuming 1:1 type modifier:substrate interactions [8c]. The experiments presented in this report suggest that the substrate to be hydrogenated may affect the order of AS of cinchonas.

2 Experimental

2.1 Materials

Cinchona alkaloids (CD, CN, QN) and solvents were purchased from Aldrich or Fluka, and used as received. EP (≥ 97 %, Fluka) was distilled in vacuum using Vigreaux-column. KPL (dihydro-4,4-dimethyl-2,3-furandione, 97 %,

Aldrich) was subjected to azeotropic distillation with toluene to remove water, then was crystallized from benzene. From the catalyst pretreatment methods (high temperature, ultrasound [11]) we applied the former procedure. The catalyst, Engelhard 5% Pt/Al_2O_3 (E4759) was pretreated in a fixed-bed reactor by flushing with 30 mL min^{-1} He at 300–673 K for 30 min then hold in 30 mL min^{-1} H_2 at 673 K for 100 min. After cooling to room temperature in H_2, the catalyst was flushed with He for 30 min and was stored under air until use.

2.2 Hydrogenations in Batch Reactor

Hydrogenations were performed in an atmospheric batch glass reactor of 10 mL volume as previously reported [10a, b]. Standard conditions were: 12.5 mg E4759 catalyst, 2.5 mL solvent, 0.5 mmol of substrate, total modifiers concentration 0.1 mM, 0.1 MPa H_2 pressure, 273 K, 900–1,000 rpm. Hydrogenations with mixtures of modifiers were carried out in T and AcOH using the same procedure as for a single modifier. The procedure used in transient behaviour measurements was as follows: hydrogenation was performed at a modifier concentration of 0.05 mM until 10–20 % conversion was achieved; at this point stirring was stopped and after 1 min a sample was taken. The second modifier was added next and hydrogenation and sampling were continued.

2.3 Hydrogenations in Flow System

Continuous hydrogenations were carried in H-Cube high-pressure continuous flow system purchased from Thales Nanotechnology Inc. [12]. The experimental set-up has been described in detail in previous publications [13]. In the tubular catalyst cartridge of 2 mm inner diameter and 30 mm length the given amount of catalyst was placed and was filled with additional alumina. The catalyst was rinsed 0.5 h with 1 mL/min flow of the corresponding solvent followed by 0.5 h pretreatment with H_2 in the same solvent. The reactant and the modifier were dissolved in the solvent and this solution was delivered to the hydrogenation system via a conventional HPLC pump (Knauer Well Chrom HPLC-pump K-120) mixed with H_2 under the desired pressure and passed through the catalyst bed obtaining an ascendant flow of the reaction components. The catalyst cartridge holder was externally cooled to 283 ± 2 K. The modifier was changed by replacing the solutions delivered to the pump. Samples of 1 mL were taken at regular time intervals from the product flow and analyzed [14]. Standard conditions were: 20 mg E4759 catalyst, solvent: T/AcOH 9/1, liquid flow 1 mL/min, modifier concentration 0.044 mM, substrate concentration 45 mM, 4 MPa H_2 pressure, 283 ± 2 K.

2.4 Product Analysis

The products were identified by mass spectrometric (HP 6890 N GC-HP 5973 MSD, HP-1MS, 60 m capillary column) analysis. Conversions and enantiomeric excesses, $ee\% = ([R] - [S]) \times 100/([R] + [S])$, were determined by gas chromatography (HP 6890 N GC-FID, 30 m long Cyclodex-B chiral capillary column, 21.65 psi He). Retention times (min): EP 343 K: 6.6 of (*R*)-EL, 7.3 of (*S*)-EL; KPL 398 K: 10.6 of (*S*)-PL, 11.2 of (*R*)-PL. The reproducibility was ± 2%. Transformation of the cinchona alkaloids was checked by ESI-MS measurements (AGILENT 1100 LC-MSD TRAP SL ion-trap MS) operated under positive ion and auto MS-MS mode as described earlier [15].

3 Results and Discussions

Experimental data reported and interpreted in detail are available from studies on the NLP in the Orito reaction with both EP [10, 16–19] and KPL [8d, 20] as substrate. NLP studies, however, have not been carried out on the two substrates under identical experimental conditions. As concerns the observations related to the AS of the cinchona alkaloids and the conclusions drawn [7d, 8–10, 16, 17], from the initial investigations it could be assumed, that the opposite order of AS of cinchonas is a result of the significantly different experimental conditions. In one case the only component present in addition to cinchona and Pt is the solvent, whereas in the other case the substrate to be hydrogenated is also present, in addition to the above listed components. Hence in the followings in the case of NLP the AS of the cinchona alkaloids was denoted with *AS*.

3.1 NLP Results Using CN-QN Modifiers Mixtures

According to the data shown in Fig. 1, in the EP hydrogenation the direction of enantioselection changes near linearly with the concentrations of the two modifiers. On the contrary, in the case of KPL hydrogenation, however, the direction of enantioselection is affected to a much higher extent by CN than by QN. In other words, in the present case it appears as if the *AS* of CN is higher than that of QN.

3.2 Transient Behaviour Measurements in Batch Reactor System

Results obtained in both solvents (T, AcOH) in the presence of the QN-CN and the CN-QN cinchona pair are shown in Figs. 2 and 3, respectively, with EP and KPL as substrates. Figure 2 reveals that (i) CN desorbs QN more

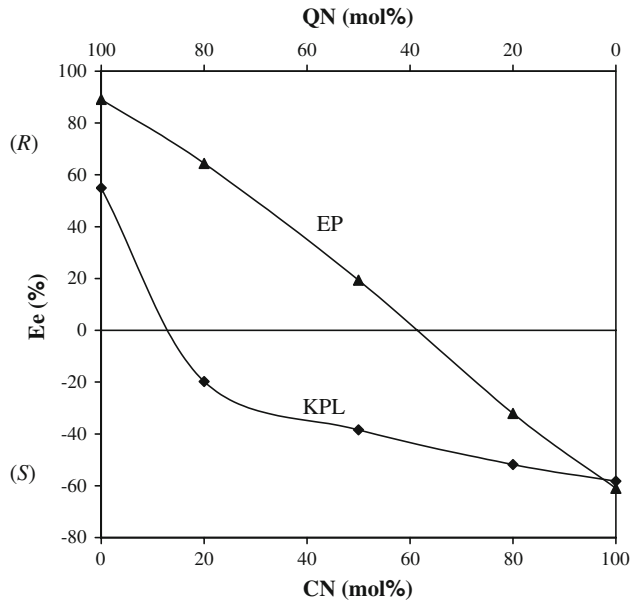


Fig. 1 Hydrogenation of EP and KPL over Pt-alumina modified by mixtures of QN + CN (standard conditions, total modifiers concentration: 0.1 mM, solvent: toluene/AcOH 9/1)

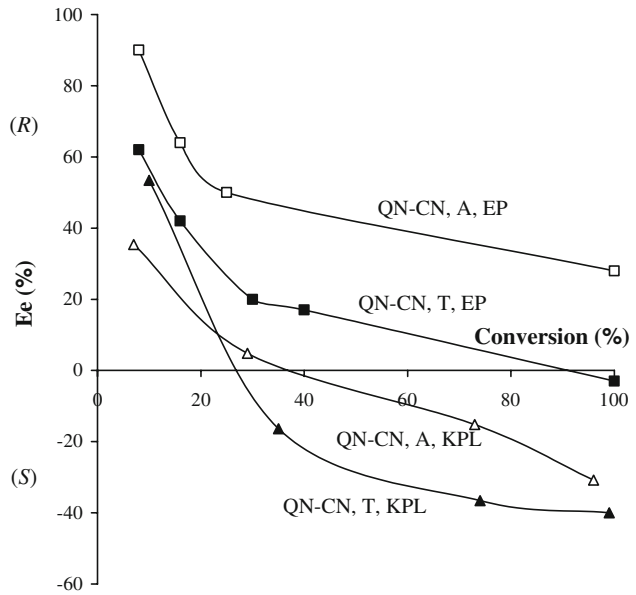


Fig. 2 Transient behaviour in the enantioselective hydrogenation of EP and KPL in toluene (T) and AcOH (A): effect of QN-CN modifiers (standard conditions, concentration of each modifier = 0.05 mM, first abbreviation-modifier used first, second abbreviation-modifier added afterwards)

readily in KPL hydrogenation than in EP hydrogenation; moreover, (ii) in the case of EP, CN is not even capable of fully desorbing QN from the surface; (iii) in KPL hydrogenation CN can nearly fully desorb QN. According to these experimental data the order of the *AS* are: CN ≈ QN in the case of EP and CN > QN in the case of KPL.

When CN was used as the first chiral modifier as illustrated in Fig. 3 (i) in EP hydrogenation CN cannot be desorbed by QN delivered as second modifier, whereas (ii) in KPL hydrogenation carried out using identical conditions as in EP hydrogenation, CN acted as if QN was not present at all. Thus, the order of the *AS* of the two cinchonas is CN ≥ QN in EP hydrogenation and CN >> QN in KPL hydrogenation. Such findings we also made earlier, however, that time we didn't see the importance of these observations, as we were concentrating on the interpretation of the "unexpected inversion" described as a novel phenomenon [10b].

3.3 Transient Measurements in Flow System

Similarly to the transient behaviour measurements in batch reactor, the continuous-flow fixed-bed reactor systems proved to be efficient for studying the NLP, resulting in insight into the dynamics of modifier competition on the Pt surface [16, 17]. These results, presented in Figs. 4–7 support the main conclusions drawn from the experimental data obtained in batch reactor.

Figure 4a displays changes in ee and conversion in EP hydrogenation under the following delivery conditions: 0–40 min, continuous delivery of the EP + CN + solvent mixture; 40–120 min, delivery of a mixture containing QN instead of CN; after 120 min, repeated delivery of a mixture containing CN. At $r_{QN} > r_{CN}$ (r = rate) there is no significant difference between the slopes of the curves

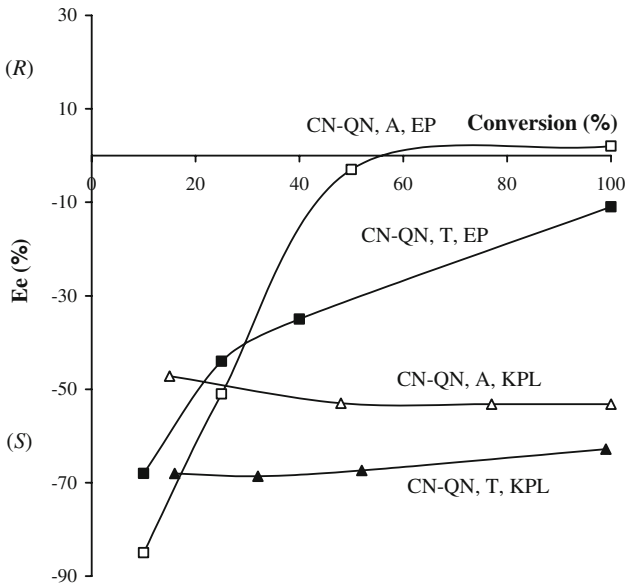


Fig. 3 Transient behaviour in the enantioselective hydrogenation of EP and KPL in toluene (T) and AcOH (A): effect of CN-QN modifiers (standard conditions, concentration of each modifier = 0.05 mM, first abbreviation-modifier used first, second abbreviation-modifier added afterwards)

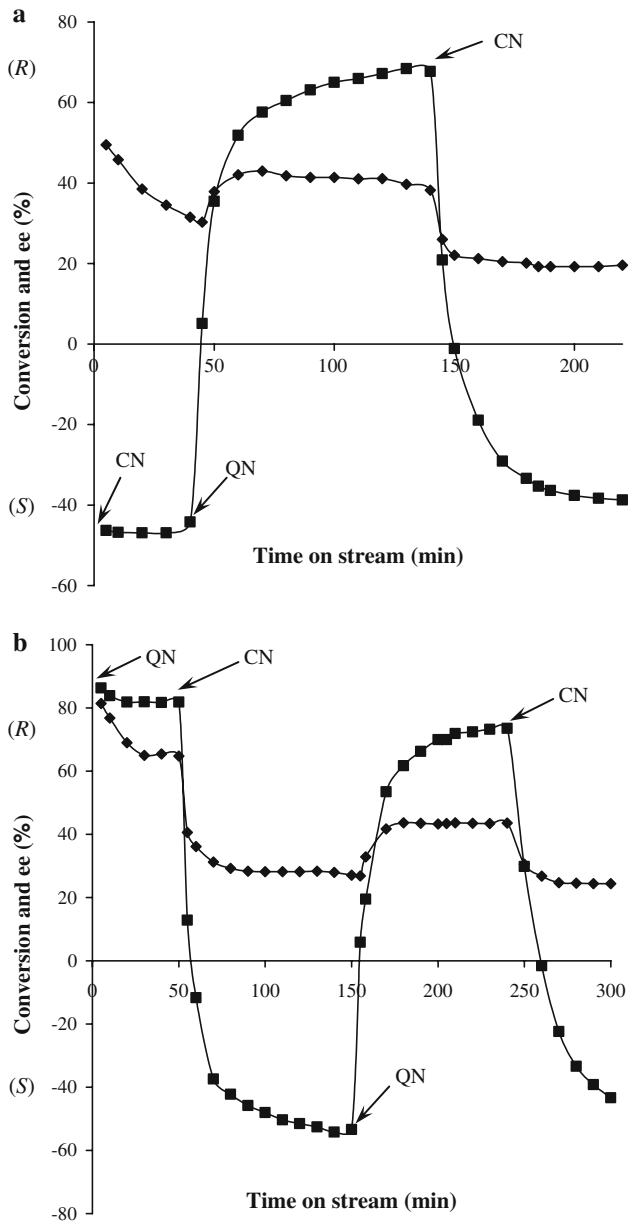


Fig. 4 (**a**) Transient behaviour in the enantioselective hydrogenation of EP in flow system: effect of CN-QN modifiers (standard conditions, squares: ee %, diamonds: conversion %). (**b**) Transient behaviour in the enantioselective hydrogenation of EP in flow system: effect of QN-CN modifiers (standard conditions, squares: ee %, diamonds: conversion %)

representing changes in the direction of enantioselection. Based on the latter, the *AS* are similar: $AS_{QN} \sim AS_{CN}$. Figure 4b shows the same parameters (r, *AS*), with the reaction series started with the addition of QN. A measurement series was also performed with the modifier pair CN-CD for the sake of comparison as presented in Fig. 5; the difference relative to the CN-QN pair was that CD had a more significant effect on CN desorption than vice versa.

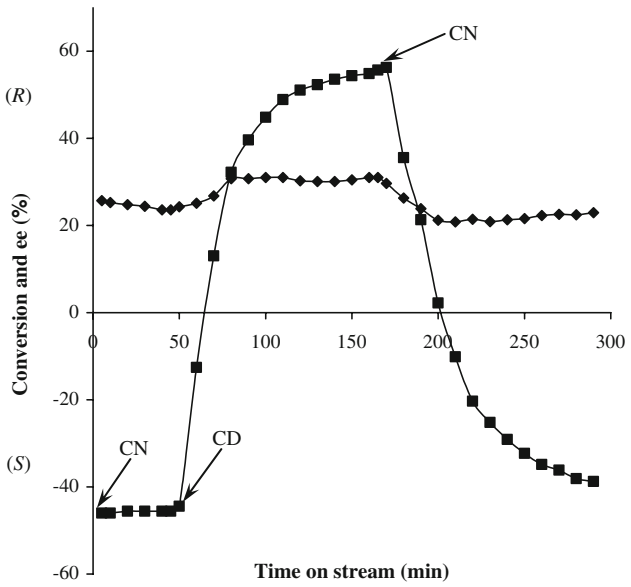


Fig. 5 Transient behaviour in the enantioselective hydrogenation of EP in flow system: effect of CN-CD modifiers (standard conditions, squares: ee %, diamonds: conversion %)

Figures 6 and 7 present the NLP in the enantioselective hydrogenation of KPL. There was a significant difference observed relative to EP, namely $r_{CN} > r_{QN}$ and $AS_{CN} > AS_{QN}$, i.e. the situation is the reverse of that observed in the case of EP. As shown by the slope of the curve recorded following the modifier changes, CN has a much larger effect on the desorption of QN than vice versa. For the sake of comparison, the effect of the CN-CD modifier pair was

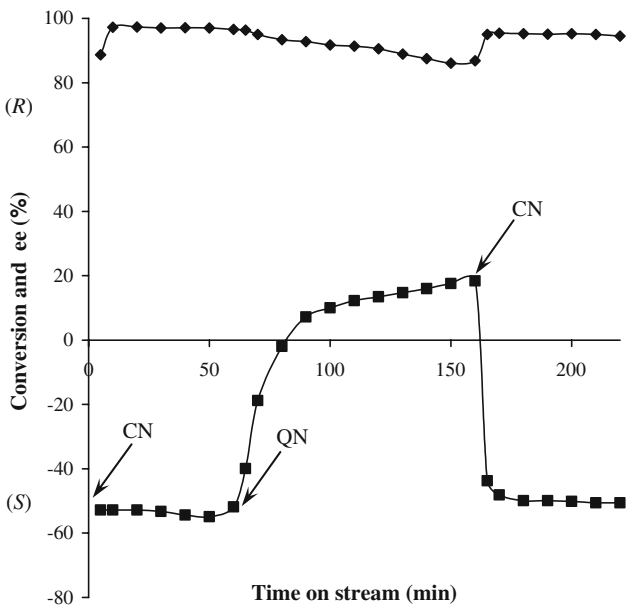


Fig. 6 Transient behaviour in the enantioselective hydrogenation of KPL in flow system: effect of CN-QN modifiers (standard conditions, squares: ee %, diamonds: conversion %)

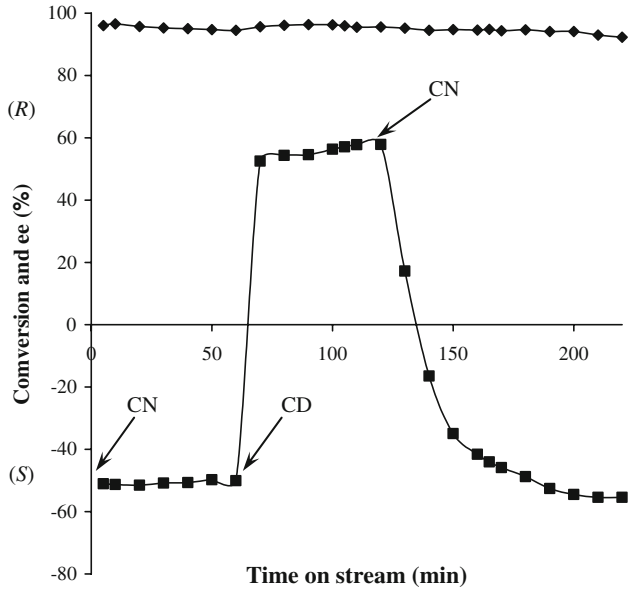


Fig. 7 Transient behaviour in the enantioselective hydrogenation of KPL in flow system: effect of CN-CD modifiers (standard conditions, squares: ee %, diamonds: conversion %)

also studied in KPL hydrogenation; the slopes of the curves allow to conclude that $AS_{CD} > AS_{CN}$ (as opposed to the pair above, where $AS_{QN} < AS_{CN}$).

To sum up the above, it can be established that a much smaller difference can be observed between the ASs of CN and QN in EP hydrogenation than in KPL hydrogenation. In other words, QN has a much smaller effect on the desorption/replacement of CN in EP hydrogenation than in KPL hydrogenation where, for example, delivery of CN to the QN-modified catalyst in identical concentration has a considerably larger effect than in the opposite order. In the latter case the catalyst functions as if QN were not present at all. The above is confirmed by all three methods used in this study.

4 Conclusion

The increase of the selectivities of the various heterogeneous catalytic [21] and organocatalytic [22] transformations is a determinant challenge in chemical research studies. Exploring the reaction mechanism is among the most important tools to solve the selectivity problems. This is especially true in case of the enantioselective reactions. Our most unexpected experimental observations as compared to earlier results may serve also this goal. These new observations are: for EP, $r_{QN} > r_{CN}$, $AS_{QN} \sim AS_{CN}$; for KPL, $r_{QN} < r_{CN}$, $AS_{QN} < AS_{CN}$. According to the NLP measurements in the hydrogenation of activated ketones over Pt catalyst the relative AS of the parent cinchonas expressed not only the adsorption characteristics of these cinchonas over Pt. Namely one cannot determine a constant order, as suggested in the most recent reports. During our work we reached to the main conclusion, that presumably not the *AS* of the cinchona alkaloids is determined by the NLP studies.

As regards the interpretation of the new experimental data observed: without going into detailed speculations, out of several possibilities (ASs of cinchonas, adsorption-desorption equilibrium, solubilities, cinchona-substrate complexes formed in liquid phase or on the surface etc.) an important role is presumably played by interactions of various types and strengths operating among the chiral modifier, solvent, hydrogen and the substrate to be hydrogenated on the Pt surface. Zaera et al. indeed drew conclusions from the adsorption-desorption processes of cinchonas (they determined the order of the AS) [9], whereas the order set up on the basis of the NLP measurements in the hydrogenation of various substrates in fact reflects in certain cases (e.g. KPL [23]) the adsorption-desorption processes of the modifier : substrate complexes being formed. The experimental data accumulated during NLP measurements were indicative mainly not of the AS of the cinchonas, but the interactions existing between the chiral modifier, solvent, hydrogen, substrate and the surface, the adsorption-desorption equilibrium, thus a complex phenomenon. Confirmation of the above interpretation of the presented observations necessitates further studies involving various spectroscopic measurements [9, 24, 25].

Acknowledgments Financial support by the Hungarian National Science Foundation (OTKA Grant T 048764, K 72065) is highly appreciated. G. S. thanks the Hungarian Academy of Sciences for the award of Bolyai János scholarship.

References

1. (a) Izumi Y (1971) Angew Chem Int Ed Engl 10:871; (b) Izumi Y (1983) Adv Catal 32:215; (c) Bartók M, Wittmann Gy, Göndös Gy, Smith GV (1987) J Org Chem 52:1139; (d) Wittmann Gy, Bartók GB, Bartók M, Smith GV (1990) J Mol Catal 60:1; (e) Osawa T, Harada T, Takayasu O (2006) Curr Org Chem 10:1513
2. (a) Orito Y, Imai S, Niwa S (1979) J Chem Soc Jpn 8:1118; (b) Orito Y, Imai S, Niwa S, Hung NG (1979) J Synth Org Chem 37:173
3. (a) von Arx M, Bürgi T, Mallat T, Baiker A (2002) Chem Eur J 8:1430; (b) Künzle N, Szabo A, Schürch M, Wang G, Mallat T, Baiker A (1998) Chem Commun 1377; (c) von Arx M, Mallat T, Baiker A (2001) Tetrahedron: Asymmetr 12:3089
4. (a) Török B, Balázsik K, Szöllösi Gy, Felföldi K, Bartók M (1999) Chirality 11:470; (b) Balázsik K, Szöri K, Felföldi K, Török B, Bartók M (2000) Chem Commun 555; (c) Balázsik K, Bartók M (2004) J Catal 224:463; (d) Török B, Balázsik K, Török M, Szöllösi Gy, Bartók M (2000) Ultrason Sonochem 7:151
5. (a) Blaser HU, Garland M, Jallet HP (1993) J Catal 144:569; (b) Studer M, Burkhardt S, Blaser HU (1999) Chem Commun 1727; (c) Török B, Felföldi K, Balázsik K, Bartók M (1999) Chem

Commun 1725; (d) Exner C, Pfaltz A, Studer M, Blaser HU (2003) Adv Synth Catal 345:1253
6. (a) Baiker A (2005) Catal Today 100:159; (b) Murzin DY, Maki-Arvela P, Toukoniitty E, Salmi T (2005) Catal Rev Sci Eng 47:175; (c) Hutchings GJ (2005) Ann Rev Mat Res 35:143
7. (a) Bartók M (2006) Curr Org Chem 10:1533; (b) Klabunovskii E, Smith GV, Zsigmond Á (2006) Heterogeneous enantioselective hydrogenation, Springer, Dordrecht; (c) Blaser HU, Studer M (2007) Accounts Chem Res 40:1348; (d) Mallat T, Orglmeister E, Baiker A (2007) Chem Rev 107:4863
8. (a) Simons KE, Meheux PA, Ibbotson A, Wells PB (1993) Stud Surf Sci Catal 75:2317; (b) Simons KE, Meheux PA, Griffiths SP, Sutherland IM, Johnston P, Wells PB, Carley AF, Rajumon MK, Roberts MW, Ibbotson A (1994) Recl Trav Chim Pays-Bas 113:465; (c) Nitta Y, Shibata A (1998) Chem Lett 2:161; (d) Balazs L, Mallat T, Baiker A (2005) J Catal 233:327
9. (a) Ma Z, Zaera F (2006) J Am Chem Soc 128:16414; (b) Ma Z, Lee I, Zaera F (2007) J Am Chem Soc 129:16083
10. (a) Bartók M, Sutyinszki M, Balázsik K, Szöllősi Gy (2005) Catal Lett 100:161; (b) Bartók M, Sutyinszki M, Bucsi I, Felföldi K, Szöllősi Gy, Bartha F, Bartók T (2005) J Catal 231:33; (c) Balázsik K, Szöllősi Gy, Bartók M (2008) Catal Lett DOI: 10.1007/s10562-008-9498-1
11. (a) Török B, Felföldi K, Szakonyi G, Bartók M (1997) Ultrason Sonochem 4:301; (b) Balázsik K, Török B, Felföldi K, Bartók M (1999) Ultrason Sonochem 5:149; (c) Bartók M, Szöllősi Gy, Balázsik K, Bartók T (2002) J Mol Catal A:Chem 177:299
12. Thales Nanotechnology H-Cube™ flow hydrogenator, see http://www.thalesnano.com
13. (a) Saaby S, Knudsen KR, Ladlow M, Ley SV (2005) Chem Commun 23:2909; (b) Desai B, Kappe CO (2005) J Comb Chem 7:641; (c) Jones RV, Godorhazy L, Varga N, Szalai D, Urge L, Darvas F (2006) J Comb Chem 8:110
14. (a) Szöllősi Gy, Hermán B, Fülöp F, Bartók M (2006) React Kinet Catal Lett 88:391; (b) Hermán B, Szöllősi Gy, Fülöp F, Bartók M (2007) Appl Catal A:Gen 331:39
15. (a) Bartók M, Bartók T, Szöllösi Gy, Felföldi K (1999) Catal Lett 61:57; (b) Bartók M, Szabó PT, Bartók T, Szöllösi Gy (2000) Rapid Commun Mass Spectrom 14:509
16. Meier DM, Mallat T, Ferri D, Baiker A (2006) J Catal 244:260
17. Meier DM, Ferri D, Mallat T, Baiker A (2007) J Catal 248:68
18. (a) Huck WR, Bürgi T, Mallat T, Baiker A (2003) J Catal 216:276; (b) Huck WR, Mallat T, Baiker A (2003) Catal Lett 87:241
19. Balázsik K, Bucsi I, Cserényi Sz, Szöllősi Gy, Bartók M (2008) J Mol Catal A:Chem 280:87
20. (a) Diezi S, Szabó A, Mallat T, Baiker A (2003) Tetrahedron: Asymmetr 14:2573; (b) Diezi S, Mallat T, Szabó A, Baiker A (2004) J Catal 228:162
21. (a) Martinek TA, Varga T, Fülöp F, Bartók M (2007) J Catal 246:266; (b) Martinek TA, Varga T, Balázsik K, Szöllősi Gy, Fülöp F, Bartók M (2008) J Catal 255:296
22. (a) Fache F, Valot F, Lemaire M (2001) In: Sheldon RA, van Bekkum H (eds) Fine chemicals through heterogeneous catalysis, Wiley, Weinheim; (b) Notheisz F, Bartók M, Ostgard D, Smith GV (1986) J Catal 101:212; (c) Molnár Á, Bucsi I, Bartók M, Resofszki G, Gáti Gy (1991) J Catal 129:303; (d) Mastalir Á, Király Z, Szöllősi Gy, Bartók M (2000) J Catal 194:146
23. (a) Berkessel A, Gröger H (2005) Asymmetric organocatalysis, Wiley-VCH, Weinheim; (b) Enders D, Balensiefer T (2004) Acc Chem Res 37:534; (c) Houk KN, List B (2004) Acc Chem Res 37:487; (d) Dalko PI, Moisan L (2004) Angewandte Chem Int Ed 43:5138; (e) Szöllősi Gy, London G, Baláspiri L, Somlai Cs, Bartók M (2003) Chirality 15:S90
24. (a) Ferri D, Bürgi T (2001) J Am Chem Soc 123:12074; (b) Kubota J, Zaera F (2001) J Am Chem Soc 123:11115; (c) Chu W, LeBlanc RJ, Williams CT (2002) Catal Commun 3:547; (d) Bakos I, Szabó S, Bartók M, Kálmán E (2002) J Electroanal Chem 532:113
25. (a) Bonalumi N, Vargas A, Ferri D, Burgi T, Mallat T, Baiker A (2005) J Am Chem Soc 127:8467; (b) Kraynov A, Suchopar A, D'Souza L, Richards R (2006) Phys Chem Chem Phys 8:1321; (c) Wahl M, von Arx M, Jung TA, Baiker A (2006) J Phys Chem B 110:21777