Catalysis Communications 11 (2010) 419–421

Contents lists available at ScienceDirect

Catalysis Communications

journal homepage: www.elsevier.com/locate/catcom

The use of new carboranylphosphite ligands in the asymmetric Rh-catalyzed hydrogenation

Sergey E. Lyubimov [a,*], Ilya V. Kuchurov [b], Andrey A. Tyutyunov [a], Pavel V. Petrovskii [a], Valery N. Kalinin [a], Sergei G. Zlotin [b], Vadim A. Davankov [a], Evamarie Hey-Hawkins [c]

[a] A.N. Nesmeyanov Institute of Organoelement Compounds, Russian Academy of Sciences, Vavilov Street 28, 119991 Moscow, Russia
[b] N.D. Zelinsky Institute of Organic Chemistry, Russian Academy of Sciences, Leninsky Prosp. 47, 119991 Moscow, Russia
[c] Institut für Anorganische Chemie, Johannisallee 29, 04103 Leipzig, Germany

ARTICLE INFO

Article history:
Received 3 August 2009
Received in revised form 11 November 2009
Accepted 12 November 2009
Available online 5 December 2009

Keywords:
Asymmetric hydrogenation
Rhodium
Supercritical carbon dioxide
Carboranylphosphite ligands

ABSTRACT

A series of new monodentate phosphite ligands based on carboranes have been synthesized and used for asymmetric Rh-catalyzed hydrogenation of prochiral olefins in CH_2Cl_2 with the result of up to 99.5% ee. High reactivities (100% conversion in 45–60 min) and enantioselectivities (up to 92%) were obtained in the hydrogenation of dimethyl itaconate in supercritical CO_2. In this case the catalytic performance is affected greatly by hydrogen and total pressures.

1. Introduction

Sterically bulky ligands play an important role in organometallic chemistry [1–9]. Carboranes are attractive synthons for the preparation of sterically congested ligands due to their significant steric bulk, stability to oxidative destruction and sufficiently simple functionalization [10,11]. Furthermore, isomeric carboranes (*ortho*-, *meta* and *para*-) have unusual electronic properties. For example, *ortho*-carboran-9-yl substituent is a powerful electron-donating group ($\delta_i = -0.23$), unlike *ortho*-carboran-1-yl which is a powerful electron acceptor ($\delta_i = +0.39$), while steric properties of the both units are equal [11]. Recently, we designed first examples of chiral mono- and bidentate phosphite-type ligands containing sterically congested carborane fragments and showed their high efficiency for the Rh-catalyzed asymmetric hydrogenation of functionalized olefins (up to 99.8% ee) [12,13]. Further examination of the catalytic activity and selectivity of the ligands shows that monodentate ligands are more effective compared to bidentate carboranylphosphite-type ligands, and electron-donating carboranyl substituents are essential for obtaining high levels of enantiodiscrimination and conversion [13–15]. Encouraged by the excellent enantioselectivities in the asymmetric hydrogenation processes and motivated by our continuing efforts in the design of novel highly modular chiral carboranylphosphite-type ligands, we have prepared novel sterically congested carborane-containing monodentate ligands for application in Rh-catalyzed hydrogenation of prochiral olefins.

2. Experimental

2-Chloro-dinaphtho[2,1-d:1′,2′-f][1,2,3]dioxaphosphepine (**1**) [16] and 2-Chloro-5,5′,6,6′,7,7′,8,8′-octahydro-dinaphtho[2,1-d:1′,2′-f][1,2,3]dioxaphosphepine (**2**) [17], 9-hydroxy-1,2-dimethylcarborane **3** and 9-hydroxy-*ortho*-carborane **4** [18] were prepared as published. Ligands **5**, **6** were synthesised analogously to the known procedures [12,14].

(*S*)-2-(1,2-dimethyl-*ortho*-carboran-9-yloxy)-dinaphtho[2,1-d:1′,2′-f][1–3]dioxaphosphepine (**5**). $^{31}P\{H\}$ NMR (121.5 MHz, $CDCl_3$): = 146.72 (q, $J_{P,B} = 14.5$ Hz). ^{11}B NMR (128.38 MHz, $CDCl_3$): −14.59 to 10.75 (m, 8B), −6.28 (d, $J = 147.8$ Hz, 1B), 10.76 (s, 1B). $^{13}C\{H\}$ NMR (100.6 MHz, $CDCl_3$): 20.65 (s, CH_3), 23.44 (s, CH_3), 59.45 (s, carb), 68.83 (s, carb), 121.93, 122.35, 122.91, 124.36 (d, $J = 4.6$ Hz), 124.48, 124.71, 125.71, 125.92, 126.80, 126.89, 128.06, 128.16, 129.24, 129.87, 130.98, 131.28, 132.49, 132.72, 147.55, 147.69 (d, $J = 4.2$ Hz) aryl all. Anal. Calc. for $C_{24}H_{27}B_{10}O_3P$: C, 57.36; H, 5.42; B, 21.51. Found: C, 57.42; H, 5.51; B, 21.47.

(*R*)-2-(*ortho*-carboran-9-yloxy)-5,5′,6,6′,7,7′,8,8′-octahydro-dinaphtho [2,1-d:1′,2′-f][1–3]dioxaphosphepine (**6**). $^{31}P\{H\}$ NMR (121.5 MHz, $CDCl_3$): = 138.01 (q, $J_{P,B} = 15.0$ Hz). ^{11}B NMR (128.38 MHz, $CDCl_3$): −19.91 to 13.13 (m, 6B), −10.35 (d, $J = 147.8$ Hz, 2B), −3.69 (d,

* Corresponding author. Tel.: +7 499 1352548; fax: +7 499 1356471.
E-mail address: lssp452@mail.ru (S.E. Lyubimov).

1566-7367/$ - see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.catcom.2009.11.012

J = 149.6 Hz 1B), 11.93 (s, 1B). ^{13}C {H} NMR (100.6 MHz, $CDCl_3$): 22.30 (CH_2), 22.34 (CH_2), 22.48 (CH_2), 22.57 (CH_2), 27.58 (CH_2), 27.67 (CH_2), 28.99 (CH_2), 29.10 (CH_2), 40.59 (s, carb), 49.92 (s, carb), 118.85 (CH ar), 119.10 (CH ar), 127.92 (C ar), 128.77 (CH ar), 129.04 (CH ar), 129.45 (d, J = 5.2 Hz, C ar), 133.53 (C ar), 134.46 (C ar), 137.00 (C ar), 138.13 (C ar), 145.44 (d, J = 3.8 Hz, C ar), 146.08 (C ar). Anal. Calc. for $C_{22}H_{31}B_{10}O_3P$: C, 54.76; H, 6.48; B, 22.40. Found: C, 54.82; H, 6.55; B, 22.44.

Substrates **9**, 10 were prepared according to the published procedures [19,20].

(*Z*)-Methyl 2-acetamido-3-(cymantrenyl)acrylate (**13**) was prepared similarly to **9**, **10** from corresponding azlactone [21]. ^1H NMR ($CDCl_3$, 300 MHz) δ 2.16 (s, 3H, CH_3 Ac), 3.81 (s, 3H, CH_3, O–Me), 4.78 (s, 2H, Cp), 5.05 (s, 2H, Cp), 6.95 (s, 1H, NH), 7.01 (s, 1H, CH). Anal. Calc. for $C_{14}H_{12}MnNO_6$: C, 48.71; H, 3.50; N, 4.06. Found: C, 48.80; H, 3.59; N, 3.98.

Dimethyl itaconate **7** and methyl 2-acetamidoacrylate **8** were obtained from Aldrich.

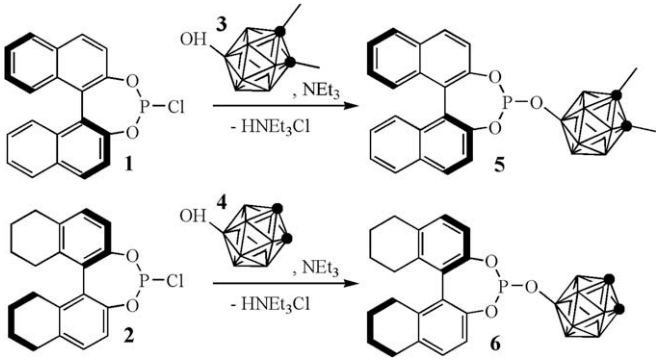
2.1. Hydrogenation of dimethyl itaconate in $scCO_2$

The catalysts were prepared by adding the corresponding monodentate ligand (0.012 mmol) to a solution of $[Rh(COD)_2]BF_4$ (2.4 mg, 0.006 mmol) in CH_2Cl_2 (0.5 ml). The solution was stirred for 5 min before removing the solvent in vacuo. The pre-formed catalysts (0.006 mmol) and substrate **7** (0.6 mmol) were placed open to air into a 10 ml autoclave. The vessel was pressurized with hydrogen and then filled with $scCO_2$ by means of a syringe-press. The mixture was allowed to equilibrate to the reaction temperature (15 min) and stirred for 45–60 min. After stirring, the vessel was slowly depressurized. The reaction products were dissolved in acetone (3 ml), the catalyst removed via a short silica gel column. The filtrate was concentrated in vacuo to afford the target product **12**.

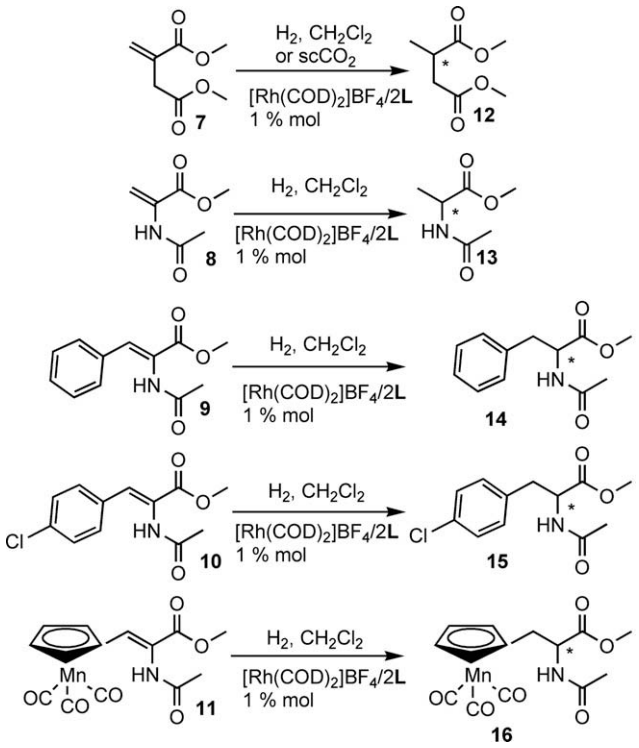
3. Results and discussion

The new monodentate phosphite **5** and **6** were synthesized by a convenient one step phosphorylation of the corresponding 9-hydroxy-1,2-dimethylcarborane **3** and 9-hydroxy-*ortho*-carborane **4**. The products were characterized by ^{31}P, ^{13}C and ^{11}B spectroscopy and by elemental analysis (see Section 2). They are white solids and are air stable under ambient conditions (Scheme 1).

Ligands **5** and **6** were first used in the Rh-catalyzed hydrogenation of dimethyl itaconate **7** (Scheme 2). The catalysts were formed in situ by mixing $[Rh(COD)_2]BF_4$ with 2 equiv. of the chiral ligand **5** or **6** in CH_2Cl_2 under argon. The catalysts exhibited excellent enantioselectivities (98 and 99.5% ee) and complete conversion of **7** (Table 1, entries 1 and 2). It should be noted that the use of



Scheme 1. Synthesis of chiral carborane-containing phosphites.



Scheme 2. Asymmetric hydrogenation of dimethyl itaconate **7** and α-dehydro amino acids esters **8**–**11**.

(*S*)-ligand **5** results in (*R*)-product **12**. The (*R*)-phosphite **6** afforded **12** in opposite absolute configuration.

To expand the utility of these ligands, we also examined the Rh-catalyzed enantioselective hydrogenation of α-dehydro amino acids esters: methyl 2-acetamidoacrylate **8**, (*Z*)-methyl 2-acetamido-3-phenylacrylate **9**, (*Z*)-methyl 2-acetamido-3-(4-chlorophenyl)acrylate **10** and (*Z*)-methyl 2-acetamido-3-cymantrenylacrylate **10** (Scheme 2). In the hydrogenation of **8** the ligands **5** and **6** showed complete conversion and ee up to 80% and 76%, respectively (Table 1, entries 3 and 4). Hydrogenation of more sterically hindered substrate **9** gave complete conversion to the phenylalanine ester **14** after 16 h, but disappointingly low ee's (30–46%) were observed (Table 1, entries 5 and 6). However, reduction of the substrate **10** with electron-withdrawing Cl-substituent on the phenyl ring gave better enantioselectivity (60% ee) in the case of ligand **5** (Table 1, entry 7). Remarkable increase of enantioselectivity (up to 90% ee and 86% ee)

Table 1
Asymmetric hydrogenation of dimethyl itaconate and α-dehydro amino acids esters (10 atm H_2, 20 °C, CH_2Cl_2).[a]

Entry	Catalyst	Substrate	t (h)	Conversion (%)[b]	ee (%)[c]
1	$[Rh(COD)_2]BF_4$/**5**	**7**	16	100	98 (*S*)
2	$[Rh(COD)_2]BF_4$/**6**	**7**	16	100	99.5 (*R*)
3	$[Rh(COD)_2]BF_4$/**5**	**8**	16	100	80 (*R*)
4	$[Rh(COD)_2]BF_4$/**6**	**8**	16	100	76 (*S*)
5	$[Rh(COD)_2]BF_4$/**5**	**9**	16	100	30 (*R*)
6	$[Rh(COD)_2]BF_4$/**6**	**9**	16	100	46 (*S*)
7	$[Rh(COD)_2]BF_4$/**5**	**10**	18	100	60 (*R*)
8	$[Rh(COD)_2]BF_4$/**6**	**10**	18	100	47 (*S*)
9	$[Rh(COD)_2]BF_4$/**5**	**11**	18	100	86 (*R*)
10	$[Rh(COD)_2]BF_4$/**6**	**11**	18	100	90 (*S*)

[a] Substrate/$[Rh(COD)_2]BF_4$/ligand = 1.0/0.01/0.02.
[b] Determined by ^1H NMR spectroscopy.
[c] Determined by HPLC (Kromasil® 5-AmyCoat, 250 × 4.6 mm column, 9/1 hexane/*i*-PrOH, 1 ml/min, 219 nm) for products **13**–**16.** Ee of **12** determined by HPLC (Daicel Chiralcel OD-H) 98/2 hexane/*i*-PrOH, 0.8 ml/min, 219 nm.

Table 2
Rh-catalyzed hydrogenation of **7** in $scCO_2$, 40 °C.

Entry	P, H_2 (atm)	Total pressure (atm)	t (min)	Conversion (%)[a]	ee (%) [b]
1	25	200	60	100	60 (*R*)
2	25	125	60	100	80 (*R*)
3	80	200	45	100	92 (*R*)

[a] Determined by ^{1}H NMR spectroscopy.
[b] Ee of **12** determined by HPLC (Daicel Chiralcel OD-H) 98/2 hexane/*i*-PrOH, 0.8 ml/min, 219 nm.

was observed in the Rh-catalyzed hydrogenation of the substrate **11** bearing strong electron-withdrawing and bulky cymantrenyl group (Table 1, entry 10), showing that in this case the electronic effect of substituents in the enamides **8**–**11** played very important role in the enantiocontrol. It should be noted, that in all the cases the (*S*)-BINOL based phosphocycle induces (*R*)-absolute configuration of the products **13**-**16** (Table 1, entries 3, 5, 7, 9), while the (*R*)-H_8-BINOL based phosphorcycle gives the products with (*S*)-configuration (Table 1, entries 4, 6, 8, 10).

Ligand **6**, which proved to be the most effective in the Rh-catalyzed hydrogenation of dimethyl itaconate **7** in CH_2Cl_2, was also tested for the hydrogenation of **7** in supercritical carbon dioxide ($scCO_2$). The use of $scCO_2$ as a solvent for asymmetric metallocomplex reactions involving hydrogen as one of the substrates is particularly attractive [22]. Recent research has demonstrated enhanced reaction rates in the Rh-catalyzed hydrogenation of prochiral olefins [12,23–25]. In this case very interesting facts were observed; a complete conversion of **7** was achieved in 45–60 min compared to 16 h in CH_2Cl_2. Moreover, the enantioselectivity of the product **12** formation strongly depends on the hydrogen partial pressure. Using the low hydrogen pressure of 25 atm gives **12** with only 60% ee at a high (200 atm) total pressure (Table 2, entry 1). Lowering the total pressure to 125 atm and using the same hydrogen loading (25 atm) significantly increased enantioselectivity (Table 2, entry 2). Further increase in enantioselectivity (up to 92% ee) was observed when high hydrogen (80 atm) and total (200 atm) pressures were employed (Table 2, entry 3).

4. Conclusions

In summary, new modular chiral ligands containing different carboranyl substituents and phosphorus centers have been synthesized. The new ligands demonstrated high enantioselectivity in the Rh-catalyzed hydrogenation of dimethyl itaconate (up to 99.8% ee in CH_2Cl_2 and up to 92% ee in $scCO_2$). In the case of $scCO_2$ the catalytic performance is affected greatly by hydrogen and total pressures. The use of the ligands in the Rh-catalyzed hydrogenation of α-dehydro amino acids esters showed from moderate to high enantioselectivities (30–90% ee), in the last case electron-withdrawing substituents in substrates are favorable for high enantiodiscrimination.

Acknowledgement

This work was supported by the Russian Foundation for Basic Research (Grant No. 09-03-12104-ofi_m) and DFG-RFBR Grant No. 09-03-91345.

References

[1] I. Ojima, Catalytic Asymmetric Synthesis, 2nd ed. Wiley-VCH, 2000.
[2] A. Boerner, Phosphorus Ligands in Asymmetric Catalysis. Wiley-VCH, 2008.
[3] Q. Zeng, H. Liu, A. Mi, Y. Jiang, X. Li, M. Choi, A. Chan, Tetrahedron 58 (2002) 8799–8803.
[4] Q. Zeng, H. Liu, A. Mi, Y. Jiang, X. Li, M. Choi, A. Chan, Tetrahedron: Asymmetry 13 (2002) 115–117.
[5] S. Wu, W. Zhang, Z. Zhang, X. Zhang, Org. Lett. 6 (2004) 3565–3567.
[6] Y. Liu, K. Ding, J. Am, Chem. Soc. 127 (2005) 10488–10489.
[7] I. Gergely, C. Hegedus, H. Gulyas, A. Szollosy, A. Monsees, T. Riermeier, J. Bakos, Tetrahedron: Asymmetry 14 (2003) 1087–1090.
[8] M.T. Reetz, Angew. Chem. Int. Ed. 47 (2008) 2556–2588.
[9] M.T. Reetz, A. Meiswinkel, G. Mehler, K. Angermund, M. Graf, W. Thiel, R. Mynott, D.G. Blackmond, J. Am, Chem. Soc. 127 (2005) 10305–10313.
[10] N.N. Godovikov, V.P. Balema, E.G. Rys, Russ. Chem. Rev. 66 (1997) 1017–1032.
[11] V.N. Kalinin, V.A. Ol'shevskaya, Russ. Chem. Bull. 57 (2008) 815–836.
[12] S.E. Lyubimov, A.A. Tyutyunov, V.N. Kalinin, E.E. Said-Galiev, A.R. Khokhlov, P.V. Petrovskii, V.A. Davankov, Tetrahedron Lett. 48 (2007) 8217–8219.
[13] S.E. Lyubimov, A.S. Safronov, A.A. Tyutyunov, V.N. Kalinin, E.E. Said-Galiev, A.R. Khokhlov, P.V. Petrovskii, P.M. Valetskii, V.A. Davankov, Russ. Chem. Bull. 57 (2008) 345–348.
[14] S.E. Lyubimov, V.N. Kalinin, A.A. Tyutyunov, V.A. Olshevskaya, Y.V. Dutikova, C.S. Cheong, P.V. Petrovskii, A.S. Safronov, V.A. Davankov, Chirality 21 (2009) 2–5.
[15] S.E. Lyubimov, V.A. Davankov, P.V. Petrovskii, E. Hey-Hawkins, A.A. Tyutyunov, E.G. Rys, V.N. Kalinin, J. Organomet. Chem. 693 (2008) 3689–3691.
[16] G. Francio, C. Arena, F. Faraone, C. Graiff, M. Lanfranchi, A. Tiripicchio, Eur. J. Inorg. Chem. (1999) 1219–1227.
[17] B. Lynikaite, J. Cvengros, U. Piarulli, C. Gennari, Tetrahedron Lett. 49 (2008) 755–759.
[18] L.I. Zakharkin, V.N. Kalinin, L.S. Podvisotskaya, Zh. Obshch. Khim. 36 (1966) 1786–1789.
[19] B.S. Jursic, S. Sagiraju, D.K. Ancalade, T. Clark, E.D. Stevens, Synth. Commun. 37 (2007) 1709–1714.
[20] H. Hoshina, H. Tsuru, K. Kubo, T. Igarashi, T. Sakurai, Heterocycles 53 (2000) 2261–2274.
[21] J.C. Brunet, E. Cuingnet, H. Gras, P. Marcincal, A. Mocz, C. Sergheraert, A. Tartar, J. Organomet. Chem. 216 (1981) 73–77.
[22] D.J. Cole-Hamilton, Adv. Synth. Catal. 348 (2006) 1341–1351.
[23] S.E. Lyubimov, E.E. Said-Galiev, A.R. Khokhlov, N.M. Loim, L.N. Popova, P.V. Petrovskii, V.A. Davankov, J. Supercrit. Fluids 45 (2008) 70–73.
[24] S.E. Lyubimov, V.A. Davankov, E.E. Said-Galiev, A.R. Khokhlov, Catal. Commun. 9 (2008) 1851–1852.
[25] S.E. Lyubimov, I.V. Kuchurov, V.A. Davankov, S.G. Zlotin, J. Supercrit. Fluids 50 (2009) 118–120.