Organic and Organometallic Chemistry

Transformations of the chiral diphosphine rhodium catalyst [(1,5-COD)Rh(−)*R,R*-DIOP]$^+CF_3SO_3^-$ under conditions of hydrogenation

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Transformation products of the cationic rhodium complex [(1,5-COD)Rh(−)*R,R*-DIOP]$^+CF_3SO_3^-$ (**1**) (COD is cycloocta-1,5-diene and DIOP is (±)-2,3-*O*-isopropylidene-2,3-dihydroxy-1,4-bis(diphenylphosphino)butane), which were obtained in its reactions with molecular hydrogen, base (NEt_3), and solvents in the absence of a substrate, were investigated by ^1H and ^{31}P NMR spectroscopy. The solvate complexes [$(Solv)_2$Rh(−)*R,R*-DIOP]$^+CF_3SO_3^-$, which were generated from complex **1** in its reaction with molecular hydrogen, underwent destruction of the diphosphine ligand with elimination of benzene and were subjected to oxidation by traces of moisture and oxygen to form the DIOP dioxide complex with Rh^I. In the absence of hydrogen, complex **1** in solutions produced the diphosphine dioxide rhodium(I) complex and mono- and binuclear rhodium(I) solvate complexes. The scheme of deactivation of the complex in the absence of the substrate was proposed. The catalytic activity of the solvate complexes [(ArH)Rh(−)*R,R*-DIOP]$^+CF_3SO_3^-$, which contain benzene, *p*-xylene, and mesitylene in the coordination sphere, was studied in hydrogenation of *Z*-α-acetamidocinnamic acid.

Key words: chiral rhodium complexes, catalysts of enantioselective hydrogenation, ^{31}P NMR spectroscopy.

Recently, we have demonstrated[1] that the activity of the cationic triflate rhodium complex [(1,5-COD)Rh(−)*R,R*-DIOP]$^+CF_3SO_3^-$ (**1**) (COD is cycloocta-1,5-diene) in hydrogenation of α-acetamidocinnamic acid with molecular hydrogen is 2—3 times higher than the activities of the rhodium complexes[2—4] containing (±)-2,3-*O*-isopropylidene-2,3-dihydroxy-1,4-bis(diphenylphosphino)butane (DIOP). The optical yield of *N*-acetyl-*R*(−)-phenylalanine reached 94%, the conversion of the substrate being 100%. The kinetic results for various specimens of complex **1** were poorly reproducible. Thus, the activity of the complex varied over a wide range from 6—20 to 6000—6650 mol H_2 (g-at. Rh h)$^{-1}$; however, the optical yields were rather high (84—94%).

To gain an understanding of the nature of the processes, which occur in the chiral catalytic system upon losing its catalytic activity, there was a need to study the transformation products of complex **1** in the reactions with other components of the system, *viz.*, with the solvent, base (NEt_3), and hydrogen in the absence of the substrate. In the present study, we examined this problem by ^1H and ^{31}P NMR spectroscopy.

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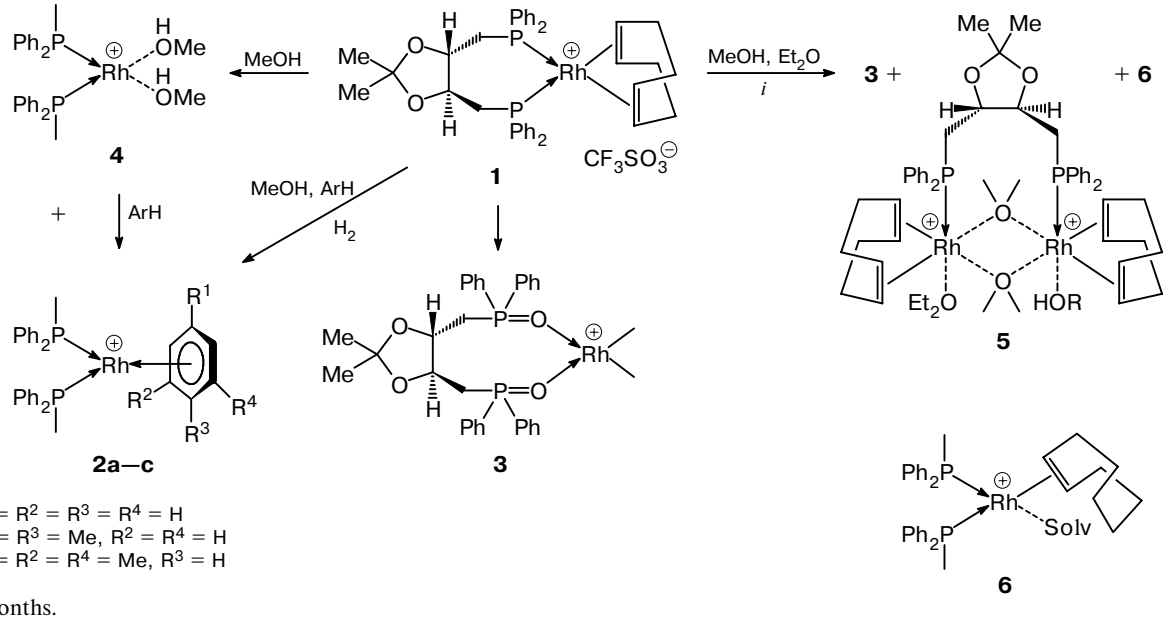
Scheme 1



a: $R^1 = R^2 = R^3 = R^4 = H$
b: $R^1 = R^3 = Me$, $R^2 = R^4 = H$
c: $R^1 = R^2 = R^4 = Me$, $R^3 = H$

i. 6 months.

The ^{31}P NMR spectrum, which was measured after treatment of a benzene—methanolic solution (C_6D_6—CD_3OD, 1 : 10) of complex **1** with molecular hydrogen at −20 °C, had a doublet signal of the initial complex ($\delta_{^{31}P}$ 11.6, $^1J_{Rh-P}$ = 144.0 Hz) and a low-intensity singlet ($\delta_{^{31}P}$ 33.5) along with a doublet at $\delta_{^{31}P}$ 28.0 ($^1J_{Rh-P}$ = 200.5 Hz) belonging to solvate complex **2a** containing the benzene-d_6 molecule in the coordination sphere (Scheme 1). A complex of the same type has been detected previously[5] in the reaction of [(1,5-COD)Rh(−)*R,R*-DIOP]$^+PPh_4^-$ with molecular hydrogen. Heating of the resulting solution to room temperature and treatment with H_2 for 30 min led to the disappearance of the signals of complexes **1** and **2a** and to a sharp increase in the intensity of the signal of complex **3** at $\delta_{^{31}P}$ 33.5.

In the ^{31}P NMR spectrum measured in CD_3OD, the signal of complex **1** was observed at $\delta_{^{31}P}$ 13.2 with the constant $^1J_{Rh-P}$ = 146.3 Hz. After the reaction of the above-mentioned solution with H_2 for 10 min, the NMR spectrum showed a signal of the initial complex as well as a doublet signal of complex **4** at $\delta_{^{31}P}$ = 43.9 ($^1J_{Rh-P}$ = 200.0 Hz), a singlet of complex **3** at $\delta_{^{31}P}$ 35.6 (it is shifted downfield by 2.1 ppm relative to the signal in the benzene—methanolic solution), and a broadened signal at $\delta_{^{31}P}$ 22—28. At the same time, signals for the protons of coordinated cyclooctadiene in the ^1H NMR spectrum disappeared, the singlet signal (at δ 1.48) of cyclooctane appeared and then became more intense, and the intensity of the signal of benzene at δ 7.3 gradually increased, the intensities of the signals of the phenyl groups of DIOP decreasing in parallel. These facts are indicative of destruction of the diphenylphosphine fragment of DIOP to form benzene (Fig. 1) and diphenylphosphide or phenylphosphinidene rhodium complexes. Apparently, the broadened signal observed in the ^{31}P NMR spectrum at $\delta_{^{31}P}$ 22—28 belongs to the last-mentioned complexes.

The addition of one equivalent of benzene to a methanolic solution, which contained complex **4** prepared *in situ*, led to a sharp decrease in the intensity of the signal at $\delta_{^{31}P}$ 43.9 and the appearance of a low-intensity doublet at $\delta_{^{31}P}$ = 29.8 with $^1J_{Rh-P}$ = 203.0 Hz. The parameters of the latter are similar to those of complex **2a**, *i.e.*, the conversion **4**→**2a** takes place (see

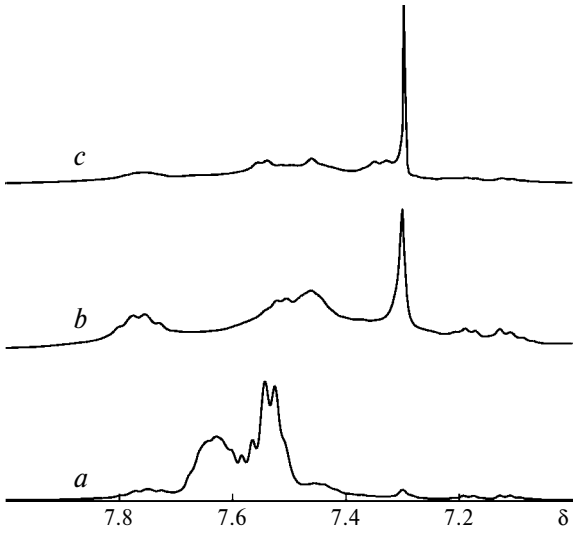
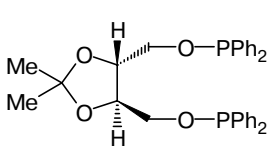


Fig. 1. ^1H NMR spectra of complex **1** in CD_3OD without treatment with H_2 (*a*) and after treatment with H_2 for 15 (*b*) and 40 min (*c*).

Scheme 1). In addition, the intensity of the singlet of complex **3** at δ_{31P} 35.6 sharply increased. This signal remained as the only signal after the additional treatment of the reaction mixture with hydrogen, a gray precipitate of metallic rhodium being formed. The addition of a threefold molar excess of triethylamine had no effect on the spectral characteristics of complex **1**. In this case, the reaction with hydrogen resulted in the same sequence of transformations with the only difference that the precipitate formed more rapidly. Complex **3** was isolated from the solution as a yellow-brown powder whose ^{31}P NMR spectrum in $CDCl_3$ has a singlet at δ_{31P} 34.4. In the NMR spectrum in DMSO-d_6, this signal is observed at δ_{31P} 28.3.

To confirm the validity of the assignment of the signals at δ_{31P} 35.6 (in CD_3OD) and 33.4 (in a $CD_3OD—C_6D_6$ mixture) to complex **3**, independent oxidation of DIOP was carried out. After oxidation of DIOP under mild conditions with two equivalents of hydrogen peroxide in acetone for 15 min, the ^{31}P NMR spectrum of the reaction product in $CDCl_3$ had two singlets at δ_{31P} 31.18 and 30.16 with the intensity ratio of 4 : 1. After oxidation under more drastic conditions (heating with an excess of H_2O_2), an additional signal at δ_{31P} 34.13 appeared in the ^{31}P NMR spectrum. Apparently, the presence of several ^{31}P signals at δ_{31P} 30—35 is indicative of the formation of products in different oxidation states, such as phosphinite **7**, phosphine oxide **8**, and phosphinate **9**.[6—8] Phosphinate **9** (δ_{31P} = 34.13) was not obtained upon oxidation under mild conditions.



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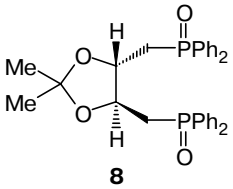

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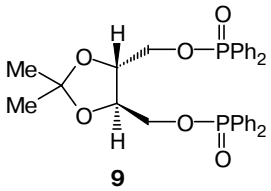

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The chemical shifts of the protons of the CH, CH_2, and CH_3 groups (see the Experimental section) in the ^1H NMR spectra of dioxide **8** and DIOP differ substantially, the signal for the methyl protons of the isopropylidene group is identical with that reported in the literature.[9,10] Hence, the signal at δ_{31P} 35.6 belongs, apparently, to phosphine oxide complex **3**, which is in agreement with the low-field shift of this signal relative to the signal of phosphine oxide **8**. It should also be noted that the position of the signal of complex **3** in the ^{31}P NMR spectrum depends noticeably on the solvent. This signal is observed at δ_{31P} 35.6 (MeOH), 33.5 ($MeOH—C_6D_6$, 10 : 1), and 28.2 (DMSO-d_6), *i.e.*, the signal is shifted upfield as the ionizing ability of the solvent decreases.

When one equivalent of itaconic acid and five equivalents of NEt_3 were added to the methanolic solution of complex **1** prior to its treatment with hydrogen, the ^{31}P NMR spectrum contained signals of complexes **1**, **3**, and **4** with the intensity ratio of 20 : 1 : 4 and the ^1H NMR spectrum showed signals belonging to the hydrogenation product of itaconic acid, *viz.*, to α-metylsuccinic acid. When the mixture was subsequently purged with hydrogen, the signal of complex **4** disappeared and the signals of complexes **1** and **3** were observed with the intensity ratio of ~3 : 1. Hence it follows that the intermediate, which was generated from methanol complex **4** and itaconic acid, reacted with hydrogen more rapidly than the initial compound. Consequently, the maximum activity of the catalyst can be achieved when the initial complex is most completely converted into the methanol complex prior to interaction of the catalyst with the substrate.

Deactivation of the catalyst also occurred upon prolonged storage of complex **1** in solution. Red-brown crystals of the artificially deactivated catalyst were isolated after prolonged storage of complex **1** in a mixture of methanol and diethyl ether. The ^{31}P NMR spectrum (Fig. 2) has the main singlet at δ_{31P} 34.7 corresponding to complex **3** along with two doublets of equal intensities at δ_{31P} 36.1 ($^1J_{P—Rh}$ = 123.8 Hz) and 46.7 ($^1J_{P—Rh}$ = 121.0 Hz) and two doublets of doublets of equal intensities at δ_{31P} 24.9 ($^1J_{P—Rh}$ = 136.6 Hz, $^2J_{P—P}$ = 41.6 Hz) and 62.6 ($^1J_{P—Rh}$ = 135.5 Hz, $^1J_{P—P}$ = 40.1 Hz). In our opinion, the former pair of the doublets, which is characterized by the nonequivalence of the phosphorus nuclei and the absence of P—P splitting, can be assigned to rhodium complex **5** because the low $^1J_{P—Rh}$ constants are typical of binuclear bridged complexes,[11] whereas the high-field signal at δ_{31P} 36.1 belongs, apparently, to the phosphorus atom in the *trans*-axial position with respect to the ether oxygen atom. The signals of the magnetically nonequivalent phosphorus nuclei at δ_{31P} 24.9 and 62.6 with the splitting constant $^1J_{P—P} \approx 40$ Hz can be assigned to the planar-square rhodium complex in which two phosphorus atoms of DIOP are in the *trans* positions with respect to two ligands of different nature (complex **6**). Complex **6**, which is analogous to that suggested previously,[5] can be generated in an insignificant amount due to partial hydrogenation of cyclooctadiene; the solvent MeOH can also serve as a donor of hydrogen. It should be noted that the rate of hydrogenation of α-acetamidocinnamic acid on the deactivated catalyst was substantially lower than that on complex **1** although the optical yields remained high.[1] This is, apparently, associated with low concentrations of catalytically active complexes **5** and **6** in the specimen.

Hence, deactivation of complex **1** in the reaction with hydrogen in the absence of the substrate is a consequence of the formation of a coordinatively unsat-

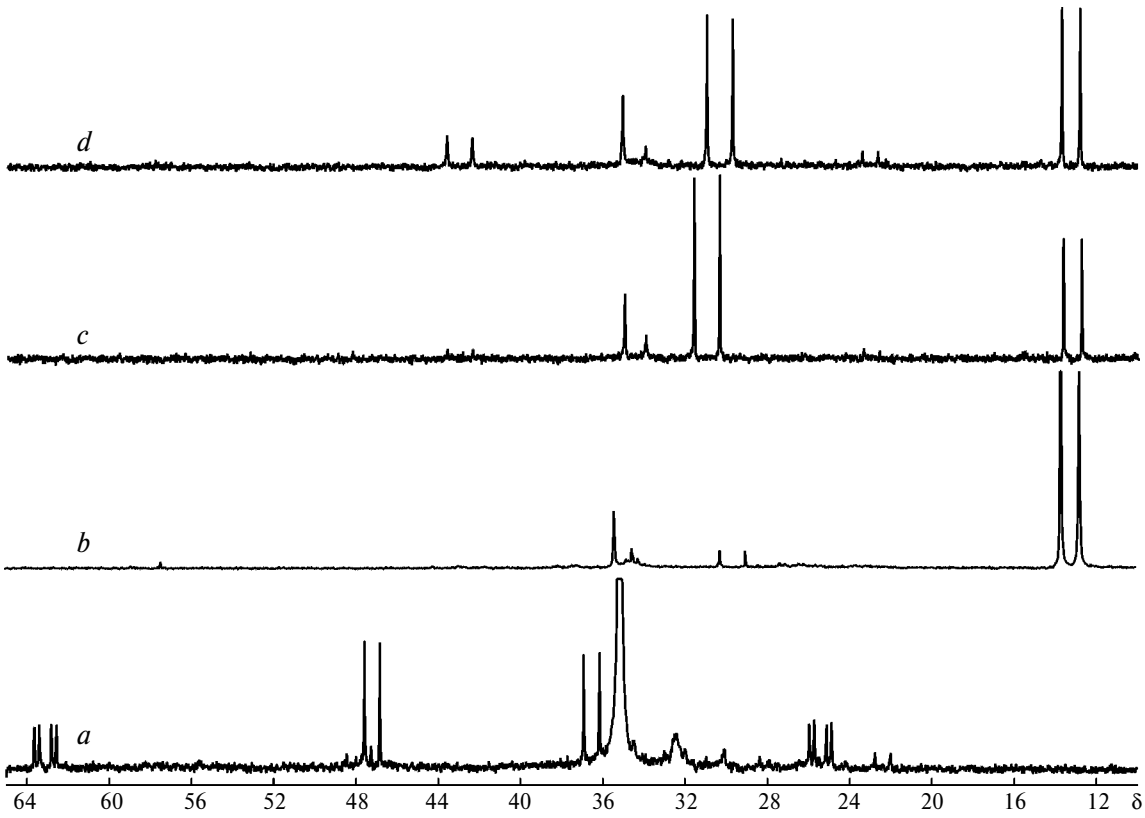

Fig. 2. ^{31}P NMR spectra of mixtures of complexes **3**, **5**, and **6** (the deactivated catalyst) (*a*) and solvate complexes containing benzene **2a** (*b*), *p*-xylene **2b** (*c*), and mesitylene **2c** (*d*).

urated species after hydrogenation of cyclooctadiene. In the absence of the strong ligand (COD), solvate complexes **2a** and **4** were formed through coordination of the solvent molecules, and the phenyl groups of DIOP were coordinated to the rhodium atom followed by the destruction of the diphenylphosphine fragment due to the *ortho*-addition of the phenyl group and its reduction to benzene. Analogous processes have been described previously for phosphine complexes of transition metals.[12,13] Due to the low (~0.001 mol L^{-1}) concentration of the catalyst, traces of moisture and oxygen, which were accumulated in the solution upon purging with hydrogen over a long period, were sufficiently large for the water and O_2 molecules to be coordinated to the Rh atom and, as a consequence, for the formation of complex **3** and phosphine oxide **8**.

One would expect that an appropriate solvent, which produces a more stable complex of type **2**, will allow one to improve the characteristics of the catalyst. We studied hydrogenation of (*Z*)-α-acetamidocinnamic acid in the presence of complex **1** in mixtures of solvents containing such arenes as benzene, *p*-xylene, and mesitylene (Table 1).

The enhancement of the optical yield in hydrogenation in *p*-xylene does not contradict Halpern's mechanism[14] according to which one of the diastereomeric olefinic intermediates is kinetically selected at the stage of the reaction with hydrogen. Apparently, the formation of the solvate *p*-xylene complex, which is more stable than the benzene complex, leads to the shift of the ratio of the diastereomeric olefinic complexes toward the minor isomer resulting in an increase in the proportion of the *R*(−) enantiomer of the product.

Table 1. Hydrogenation of (*Z*)-α-acetamidocinnamic acid on complex **1**[a]

Arene	Conversion (%)	Optical yield (%)	R_{spec}[b]
Benzene	100	84.3±0.5	2220
p-Xylene	100	88.4±0.5	2340
Mesitylene	17.3	77.8±1.3	346

[a] Conditions: an arene—MeOH solvent mixture (1 : 3), p_{H_2} = 1 atm, t = 20 °C. [b] R_{spec}/mol H_2 (g-at. Rh h)$^{-1}$.

The initial specific rate of hydrogenation of (*Z*)-α-acetamidocinnamic acid in a mesitylene—MeOH mixture is an order of magnitude lower than in those with benzene and *p*-xylene, and hydrogenation ceased when the conversion of the substrate reached ~17%; the optical yield of *R*(−)-*N*-acetylphenylalanine was only 78%.

With the aim of obtaining additional information on the nature of the complexes, we studied the reaction of complex **1** with molecular hydrogen in

p-xylene—CD_3OD and mesitylene—CD_3OD mixtures (the arene content was 5%) by ^{31}P NMR spectroscopy. The spectra of the solvate complexes with various arenes as well as the spectrum of the deactivated catalyst are shown in Fig. 2. In the case of *p*-xylene, the ^{31}P NMR spectrum has signals of complexes **1** and **3** as well as a doublet at δ_{31P} 31.01 ($^1J_{Rh-P}$ = 201.2 Hz) belonging to complex **2b**, which contains the *p*-xylene molecule in the coordination sphere. In the case of mesitylene, arene complex **2c** was formed along with complexes **1**, **3**, and **4**. Complex **2c** gives a doublet signal at δ_{31P} 30.3 with $^1J_{Rh-P}$ = 204.2 Hz. Judging from the positions of the signals of the solvate complexes, the bond between *p*-xylene and the rhodium atom is the weakest one, which facilitates coordination of the substrate and the interconversion of olefinic intermediates resulting in the maximum optical yield (see Table 1).

Hence, the nature of the arene ligand exerts a significant effect on the activity and enantioselectivity of complex **1** in hydrogenation of prochiral substrates.

Experimental

The IR spectra were recorded on a Specord IR 75 instrument. The NMR spectra were measured on a Bruker DPX-400 spectrometer operating at 400 (^1H) and 162 MHz (^{31}P) in the range from +15 to −25 ppm (^1H) and from +300 to −150 ppm (^{31}P) with HMDS as the internal standard. The chemical shifts are given relative to Me_4Si (^1H) and H_3PO_4 (^{31}P). The specific optical rotation of the products was determined on a Polamat A instrument at 546 nm and was scaled to the wavelength of 58 m using the coefficient of 1.17543. The solvents used in the experiments were thoroughly purified and degassed. All syntheses were carried out under an atmosphere of argon with the use of a system combining the supply of the purified gas and the possibility to produce rarefaction.

Complex **1** was synthesized according to a procedure similar to that described[15] for the preparation of the perchlorate complex [Rh(*S*,*S*-chiraphos)(NBD)]$^+ClO_4^-$.

Complex **3** was prepared by purging hydrogen through a solution of complex **1** (26.3 mg, $3.2 \cdot 10^{-5}$ mol) in methanol (1.5 mL) for 30 min. The solvent was removed from the resulting red-brown solution and the yellow-brown residue was dried by heating *in vacuo* for 1 h. ^1H NMR ($CDCl_3$), δ: 1.24 (s, 6 H, CH_3); 2.62 and 2.87 (both m, 2 H each, CH_2); 4.30 (m, 2 H, CH); 7.30—7.75 (m, 20 H, Ph). ^{31}P NMR, δ: 34.40 ($CDCl_3$); 28.33 (DMSO-d_6). IR (KBr pellets), ν/cm^{-1}: 505, 520, 625, 690, 745, 1023, 1156, 1236, 1259, 1435.

Phosphine oxide **8** was synthesized by the reaction of a solution of DIOP (50 mg, $1 \cdot 10^{-3}$ mol) in acetone (50 mL) with two equivalents of H_2O_2 for 15 min. The reaction product was isolated and dried and a finely crystalline white compound was obtained, m.p. 182—188 °C. ^1H NMR ($CDCl_3$), δ: 1.14 (s, 6 H, CH_3); 2.63 and 2.87 (both m, 2 H each, CH_2); 4.18 (m, 2 H, CH); 7.43—7.78 (m, 20 H, Ph). For comparison, the ^1H NMR spectrum of DIOP has signals of these groups at δ 1.33, 2.30, 2.42, 3.89, and 7.24—7.43, respectively. ^{31}P NMR ($CDCl_3$), δ: 31.18, 30.16. IR (KBr pellets), ν/cm^{-1}: 530, 690, 715, 1108, 1180, 1435.

The specimen of the artificially deactivated catalyst was obtained upon storage of complex **1** in an MeOH—Et_2O solvent mixture (1 : 1) for 6 months.

The substrates were hydrogenated with intense stirring in a glass temperature-controlled long-necked reactor connected with a manometer and a system for supplying hydrogen. The gas was purified and dried according to a standard procedure. The products were isolated and analyzed as described previously.[1]

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