

Asymmetric Hydrogenation of α -Keto Phosphonates with Chiral Palladium Catalysts

Nataliya S. Goulioukina,^{*[a]} Grigorii N. Bondarenko,^[a] Alexei V. Bogdanov,^[a]
Konstantin N. Gavrilov,^[b] and Irina P. Beletskaya^{*[a]}

Keywords: Asymmetric catalysis / Hydrogenation / Phosphonates / Palladium

Under atmospheric hydrogen pressure, a catalytic amount of palladium(II) trifluoroacetate and (*R*)-MeO-BIPHEP in 2,2,2-trifluoroethanol promoted the asymmetric hydrogenation of diisopropyl α -keto phosphonates **1** to afford the corresponding α -hydroxy phosphonates **2** in excellent yields and with a

moderate enantioselectivities of up to 55 % *ee*. Racemic α -aryl- α -hydroxy phosphonates can be prepared by using palladium on carbon as the catalyst.

(© Wiley-VCH Verlag GmbH & Co. KGaA, 69451 Weinheim, Germany, 2009)

Introduction

Chiral nonracemic α -hydroxy phosphonates are an important class of biologically active compounds that have a wide range of activities and are of interest in the design of drugs and bioregulators.^[1] They also serve as convenient precursors for a variety of biologically significant α -substituted phosphonates,^[2] in particular, chiral α -amino phosphonates.^[3]

Among the catalytic methods for the asymmetric synthesis of α -hydroxy phosphonates^[4] the enantiofacial hydrophosphonylation of carbonyl compounds with dialkyl phosphite (the Pudovik reaction) is the best elaborated.^[5,6] The alternative approach based on the enantioselective reduction of easily available α -keto phosphonates is less studied and limited to oxazaborolidine-catalyzed borane reduction.^[2a,3b,7] Surprisingly, the catalytic enantioselective reduction of α -keto phosphonates with cheap hydrogen gas has not been described, notwithstanding the fact that the asymmetric hydrogenation of β -keto phosphonates^[8] and α - and β -keto esters^[9] using chiral Ru and Rh catalysts has been very successful. The possible reason for this may be the lability of α -keto phosphonates in the presence of some transition-metal complexes.^[10] In the case of enolizable α -keto phosphonates, high *ees* were obtained in the Rh-catalyzed hydrogenation of the corresponding enol ester phosphonates,^[11] but the asymmetric hydrogenation of non-enolizable α -keto phosphonates still remains a challenging task.

Recently we reported^[12a] the enantioselective hydrogenation of α -imino phosphonates using $[\text{Rh}(\text{COD})_2]^+ \text{SbF}_6^-$ / (*R*)-BINAP as the catalyst, but all our attempts to extend the method to α -keto phosphonates have been unsuccessful because in these cases P–C bond cleavage became the predominant process.^[12b] However, we have shown that the hydrogenation of ring-substituted diethyl benzoylphosphonates can be performed by using heterogeneous Pd catalysts.^[13] This result inspired us to explore palladium catalysis in the homogeneous asymmetric hydrogenation of α -keto phosphonates. Herein we wish to report our preliminary results.

Results and Discussion

Chiral palladium complexes are especially potent for a broad range of enantioselective transformations,^[14] but until recently very little attention has been paid to their application in homogeneous hydrogenation reactions. In the last decade $\text{Pd}(\text{OCOCF}_3)_2$ /bis-phosphane has emerged as a highly efficient catalytic system for the asymmetric hydrogenation of the imine bond^[15] as well as functionalized ketones,^[16] so we become interested in exploring its use in the hydrogenation of α -keto phosphonates.

We chose diethyl benzoylphosphonate (**1a**) as a representative substrate for a preliminary screening of chiral ligands (Figure 1) and carried out the initial experiments in 2,2,2-trifluoroethanol (TFE) under 50 bar of hydrogen at room temp. The reactions were monitored by ³¹P NMR spectroscopy: The disappearance of the signal of **1a** at δ_{P} = –0.7 ppm and the emergence of the peak of diethyl [hydroxy(phenyl)methyl]phosphonate (**2a**) at δ_{P} = 22.1 ppm indicated a smooth reaction with no appreciable side-products.

The results obtained (Table 1) showed that of the tested *C*₂-symmetric bis-phosphane ligands the atropoisomeric

[a] Department of Chemistry, Moscow State University, Leninskie Gory, GSP-1, Moscow 119991, Russia
Fax: +7-495-939-1854
E-mail: goulioukina@org.chem.msu.ru
beletskaya@org.chem.msu.ru

[b] Department of Chemistry, Ryazan State University, 46 Svoboda str., Ryazan 390000, Russia
Supporting information for this article is available on the WWW under <http://www.eurjoc.org/> or from the author

60 bar of hydrogen (Table 3). As we have previously reported for diethyl acetylphosphonate,^[13] the hydrogenation of aliphatic **1h,i** does not occur in the presence of Pd/C; these substrates slowly decomposed with the formation of diisopropyl phosphite.

Conclusions

We have demonstrated a conceptually new approach to the synthesis of racemic and optically active α -hydroxy phosphonates by palladium-catalyzed hydrogenation of easily available α -keto phosphonates by molecular hydrogen. Palladium on carbon can be used as the catalyst for the synthesis of racemic ring-substituted α -hydroxybenzylphosphonates. The use of a catalytic amount of Pd(OCOCF₃)₂/(*R*)-MeO-BIPHEP in TFE resulted in the homogeneous asymmetric hydrogenation of α -aryl- α -keto and α -alkyl- α -keto phosphonates in excellent yields and with moderate enantioselectivities even at atmospheric hydrogen pressure, the procedure being very easy to handle. This method appears to be particularly promising for the preparation of optically active α -hydroxy phosphonates containing a quaternary β -carbon atom. Our ongoing experiments are focused on the fine-tuning of the structure of chiral ligands to improve the optical yield of the reaction and will be reported in due course.

Experimental Section

General: Optical rotations were measured with a VNIKI-Produmsh AI-EPO polarimeter in a 0.25 dm cell at 20 °C. Mass spectra (EI) were recorded with a Varian MAT 311 spectrometer. Elemental analyses were performed by using a Carlo-Erba autoanalyzer. The melting points were measured with an Electrothermal 9100 indicator in a sealed capillary. TLC was carried out on 0.20 mm thick Macherey–Nagel plates (ALUGRAM® SIL G/UV₂₅₄).

Methanol was dried with magnesium methoxide followed by distillation. 2,2,2-Trifluoroethanol (TFE) (P&M-Invest) was distilled from anhydrous CaSO₄ and THF from sodium benzophenone ketyl. Triethyl phosphite (Merck) and triisopropyl phosphite^[24] were treated with Na and then distilled under reduced pressure. (*S*)-(+)-2-(6-Methoxy-2-naphthyl)propanoyl chloride was obtained from (*S*)-(+)-2-(6-methoxy-2-naphthyl)propanoic acid {(*S*)-naproxen, [α]_D²⁰ = +66 (*c* = 1, CHCl₃), Akrihin} following a previously procedure.^[25] Palladium(II) trifluoroacetate was prepared according to a literature procedure.^[26] Palladium on carbon (10% Pd; Aldrich), (*R*)-(+)-BINAP (Dalchem), (*R*)-(+)-TolBINAP (Dalchem), (*R*)-(+)-MeO-BIPHEP (Aldrich), (*S,S*)-(-)-CHIRAPHOS (Dalchem) and (*S,S*)-(+)-Me-DuPhos (Aldrich) were used without purification.

(3*R*,4*R*)-3,4-Bis[(2'*R*,5'*S*)-3'-phenyl-1',3'-diaz-2'-phosphabicyclo[3.3.0]oct-2'-yloxy]-1-benzylpyrrolidine-2,5-dione (L6): A solution of (3*R*,4*R*)-1-benzyl-3,4-dihydroxypyrrolidine-2,5-dione^[27] (1.11 g, 5 mmol) in THF (15 mL) was added dropwise at 20 °C over 20 min to a vigorously stirred solution of (2*R*,5*S*)-2-chloro-3-phenyl-1,3-diaz-2-phosphabicyclo[3.3.0]octane^[28] (2.41 g, 10 mmol) and Et₃N (1.45 mL, 10.4 mmol) in THF (25 mL). The mixture was then heated to the boiling point, stirred for 1.5 h and cooled to 20 °C.

Solid Et₃N·HCl was filtered off and the filtrate was concentrated in vacuo (40 Torr). The residue was purified by flash chromatography (silica gel, hexane/EtOAc, 5:1) to furnish the product as a light-yellow solid; yield: 2.20 g (70%). MS: *m/z* (%) = 629 (8) [M]⁺, 408 (100) [M – C₁₁H₁₄N₂OP]⁺. C₃₃H₃₇N₅O₄P₂ (629.63): calcd. C 62.95, H 5.92, N 11.12; found C 63.21, H 6.0, N 10.96.

α -Keto phosphonates **1a–i** were synthesized by standard Arbuzov reaction of acyl chlorides with trialkyl phosphites^[7a,29] and purified by distillation or recrystallization; their spectral characteristics are given in the Supporting Information.

Optimization of the Reaction Conditions for the Asymmetric Hydrogenation Reaction. General Procedure: A Schlenk vessel was charged with palladium(II) trifluoroacetate (2.4 mg, 7.2 μ mol), a chiral ligand (7.4 μ mol if bidentate or 14.8 μ mol if monodentate), and anhydrous acetone (3 mL) under argon. The mixture was stirred at room temp. for about 30–40 min. The solvent was removed under vacuum. Deaerated TFE (3 mL) and substrate **1a–c** (0.144 mmol) were added under argon to the colored solid residue and the mixture was stirred for 10 min. The resulting solution was transferred with a syringe into a stainless-steel autoclave filled with hydrogen. The Schlenk vessel was washed with TFE (0.5 mL), which was added to the main solution. The autoclave was sealed, pressurized with H₂, and the reaction mixture stirred under the desired conditions (pressure and temperature) for 6 h. At the end of the experiment, the reaction mixture was evaporated on a rotavapor and the residue was dissolved in CDCl₃ (1 mL). The resulting solution was divided into two equal portions. The first one was analyzed by ³¹P NMR spectroscopy to determine the conversion and the yield of the desired product **2a–c**. The second one was treated with anhydrous pyridine (0.2 mL) and (*S*)-(+)-2-(6-methoxy-2-naphthyl)propanoyl chloride (45 mg, 0.181 mmol) and analyzed by ³¹P NMR to determine the enantiomeric excess.

Asymmetric hydrogenation under atmospheric hydrogen pressure (including preparative experiments) was performed in a similar manner, a simple reactor, outlined below, being used instead of the autoclave.

Diisopropyl (*S*)-(-)-[Hydroxy(phenyl)methyl]phosphonate (2b): Deaerated TFE (3 mL) and substrate **1b** (39.0 mg, 0.144 mmol) were added under argon to a sample of the catalyst prepared in a Schlenk vessel from Pd(OCOCF₃)₂ (2.4 mg, 7.2 μ mol) and (*R*)-(+)-MeO-BIPHEP (4.3 mg, 7.4 μ mol), as described above, and the mixture was stirred for 10 min. The resulting solution was transferred into the hydrogenation unit composed of a round-bottomed flask equipped with a magnetic stirrer, a reflux condenser with a three-way adapter, a gas bubbler, and a long gas inlet tube passing through the condenser to the bottom of the flask, and filled with dry argon. The Schlenk vessel was washed with TFE (0.5 mL), which was added to the main solution. The argon supply was stopped and hydrogen was passed through the reactor using the same inlet tube. The reaction mixture was stirred at 80 °C for 6 h under a weak flow of hydrogen and then cooled. The solvent was removed under reduced pressure. The residue was dissolved in CDCl₃ and analyzed by ³¹P NMR spectroscopy. The yield of **2b** thus determined was 97%. The product **2b** was purified by preparative TLC (CH₂Cl₂/MeOH, 40:1, *R*_f = 0.20). Isolated yield: 30.9 mg (79%), 45% *ee* [determined for the (*S*)-naproxen ester]. [α]_D²⁰ = –12.0 (CHCl₃, *c* = 1.0) {lit.: [α]_D²⁰ = –12.0 (CHCl₃, *c* = 1.0) for 45% *ee* (*S*).^[7a] [α]_D²⁰ = –16.0 (CHCl₃, *c* = 1.0) for 60% *ee* (*S*).^[22] [α]_D²⁰ = –17.3 (CHCl₃, *c* = 1.0) for 65% *ee* (*S*).^[7b] }

Diisopropyl (*S*)-(-)-[Hydroxy(4-fluorophenyl)methyl]phosphonate (2d): Synthesized similarly to **2b** in 99% yield by the hydrogenation of **1d** (41.5 mg, 0.144 mmol). Isolated yield: 40.1 mg (96%), 50%

ee, $[a]_D^{20} = -112.8$ (CHCl_3 , $c = 1.0$), $R_f = 0.19$ ($\text{CH}_2\text{Cl}_2/\text{MeOH}$, 40:1).

Diisopropyl (S)-(-)-[Hydroxy(4-methoxyphenyl)methyl]phosphonate (2e): Synthesized similarly to **2b** in 99% yield by the hydrogenation of **1e** (43.2 mg, 0.144 mmol). Isolated yield: 33.2 mg (76%), 55% *ee*, $[a]_D^{20} = -12.3$ (CHCl_3 , $c = 0.8$) {lit.: $[a]_D^{20} = -10.0$ (CHCl_3 , $c = 0.8$) for 45% *ee* (S),^[7a] $[a]_D^{20} = -12.3$ (CHCl_3 , $c = 0.8$) for 55% *ee* (S)^[7b]}, $R_f = 0.14$ ($\text{CH}_2\text{Cl}_2/\text{MeOH}$, 40:1).

Diisopropyl (S)-(-)-[Hydroxy(4-methylphenyl)methyl]phosphonate (2f): Synthesized similarly to **2b** in 98% yield by the hydrogenation of **1f** (41.0 mg, 0.144 mmol). Isolated yield: 39.0 mg (94%), 51% *ee*, $[a]_D^{20} = -13.4$ (CHCl_3 , $c = 0.8$), $R_f = 0.17$ ($\text{CH}_2\text{Cl}_2/\text{MeOH}$, 40:1).

Diisopropyl (S)-(-)-[Hydroxy(2-methylphenyl)methyl]phosphonate (2g): Synthesized similarly to **2b** in 95% yield by the hydrogenation of **1g** (41.0 mg, 0.144 mmol). Isolated yield: 39.2 mg (95%), 50% *ee*, $[a]_D^{20} = -35.2$ (CHCl_3 , $c = 0.9$) {lit.: $[a]_D^{20} = -25.3$ (CHCl_3 , $c = 0.8$) for 41% *ee* (S),^[7c] $[a]_D^{20} = -47.0$ (CHCl_3 , $c = 0.9$) for 76% *ee* (S),^[7a,c] $[a]_D^{20} = -60.0$ (CHCl_3 , $c = 0.9$) for 97% *ee* (S)^[7b,c]}, $R_f = 0.19$ ($\text{CH}_2\text{Cl}_2/\text{MeOH}$, 40:1).

Diisopropyl (S)-(+)-[Hydroxy(1-adamantyl)methyl]phosphonate (2h): Synthesized similarly to **2b** in 100% yield by the hydrogenation of **1h** (47.3 mg, 0.144 mmol). Isolated yield: 45.2 mg (95%), 34% *ee*, $[a]_D^{20} = +4$ (MeOH , $c = 1.0$).

Diisopropyl (S)-(+)-1-Hydroxyethylphosphonate (2i): Synthesized similarly to **2b** in 96% yield by the hydrogenation of **1i** (40.0 mg, 0.192 mmol) in TFE (5 mL) in the presence of a catalyst prepared from $\text{Pd}(\text{OCOCF}_3)_2$ (3.2 mg, 9.2 μmol) and (*R*)-(+)-MeO-BIPHEP (5.7 mg, 9.8 μmol). Isolated yield: 29.6 mg (73%), 33% *ee*, $[a]_D^{20} = +2.2$ (acetone, $c = 0.9$) {lit.^[21] $[a]_D^{20} = +1.46$ (acetone) for 20% *ee* (S), $[a]_D^{20} = +5.81$ (acetone) for 87% *ee* (S), $[a]_D^{20} = +5.92$ (acetone) for 89% *ee* (S), $[a]_D^{20} = -1.21$ (acetone) for 19% *ee* (R), $[a]_D^{20} = -6.03$ (acetone) for 90% *ee* (R)}.

Diisopropyl (±)-[Hydroxy(phenyl)methyl]phosphonate [(±)-2b]: Compound **1b** (400 mg, 1.48 mmol) in dry methanol (32 mL) and 10% Pd/C (80 mg, 5 mol-%) were placed in a stainless-steel autoclave with a glass insert equipped with a magnetic stirrer and filled with dry argon. The autoclave was sealed, flushed three times with hydrogen, and pressurized with H_2 to 30 bar. The reaction mixture was stirred at room temperature for 2 h. At the end of the experiment the catalyst was filtered off using a short pad of silica gel. The mother liquor was evaporated under reduced pressure and the residue was dissolved in CDCl_3 . ^{31}P NMR analysis showed a 91% yield of (±)-**2b**. After recrystallization from diethyl ether the yield of spectrally pure (±)-**2b** was 279 mg (69%), m.p. 92 °C.^[30]

Diisopropyl (±)-[Hydroxy(4-fluorophenyl)methyl]phosphonate [(±)-2d]: Compound (±)-**2d** was synthesized similarly to (±)-**2b** in 96% yield by the hydrogenation of **1d** (400 mg, 1.39 mmol) in dry methanol (32 mL) in the presence of 10% Pd/C (74 mg, 5 mol-%). After recrystallization from diethyl ether the yield of pure (±)-**2d** was 351 mg (87%), m.p. 93 °C.^[31] $\text{C}_{15}\text{H}_{20}\text{FO}_4\text{P}$ (290.27): calcd. C 53.79, H 6.94; found C 53.55, H 6.83.

Diisopropyl (±)-[Hydroxy(4-methoxyphenyl)methyl]phosphonate [(±)-2e]: Compound (±)-**2e** was synthesized similarly to (±)-**2b** by the hydrogenation of **1e** (400 mg, 1.33 mmol) in dry methanol (32 mL) in the presence of 10% Pd/C (71 mg, 5 mol-%). The yield of spectrally pure (±)-**2e** was 402 mg (100%), m.p. 141–142 °C.^[30b]

Diisopropyl (±)-[Hydroxy(4-methylphenyl)methyl]phosphonate [(±)-2f]: Compound (±)-**2f** was synthesized similarly to (±)-**2b** by the hydrogenation of **1f** (100 mg, 0.35 mmol) in dry methanol (8 mL) in the presence of 10% Pd/C (19 mg, 5 mol-%). The reaction was

performed at 15 bar hydrogen pressure. The yield of spectrally pure (±)-**2f** was 101 mg (100%), m.p. 115–116 °C.^[32]

Diisopropyl (±)-[Hydroxy(2-methylphenyl)methyl]phosphonate [(±)-2g]: Compound (±)-**2g** was synthesized similarly to (±)-**2b** in 94% yield by the hydrogenation of **1g** (50 mg, 0.18 mmol) in dry methanol (4 mL) in the presence of 10% Pd/C (19 mg, 5 mol-%). The reaction was performed at 60 bar hydrogen pressure. Spectrally pure (±)-**2g** (41 mg, 81%) was isolated by TLC ($\text{CH}_2\text{Cl}_2/\text{MeOH}$, 40:1), m.p. 92 °C.^[33]

The spectroscopic data for (±)-**2b,d–g** were in agreement with those for **2b,d–g**.

Supporting Information (see also the footnote on the first page of this article): Spectral data of compounds **1**, **2b,d–i** and **L6**.

Acknowledgments

Financial support of this work by the International Association for the promotion of co-operation with scientists from the New Independent States of the former Soviet Union (INTAS) (Grant No. 05-1000008-8064) and the Russian Foundation for Basic Research (Grants No. 04-03-39017 and No. 08-03-00416-a) is gratefully acknowledged.

- [1] O. I. Kolodiaznyy, *Russ. Chem. Rev. (Engl. Trans.)* **2006**, *75*, 227–253.
- [2] a) M. Bubenik, P. Préville, J. Dugas, G. Attardo, L. Chan, *Tetrahedron Lett.* **2003**, *44*, 8261–8263; b) L. Maier, *Phosphorus Sulfur Silicon Relat. Elem.* **1993**, *76*, 119–122; c) M. Overhand, H. R. Stuivenberg, E. Pieterman, L. H. Cohen, R. E. W. van Leeuwen, A. R. P. M. Valentijn, H. S. Overkleeft, G. A. van der Marel, J. H. van Boom, *Bioorg. Chem.* **1998**, *26*, 269–282; d) R. N. Patel, A. Banerjee, L. J. Szarka, *Tetrahedron: Asymmetry* **1997**, *8*, 1055–1059; e) M. Gulea, F. Hammerschmidt, P. Marchand, S. Masson, V. Pisljagic, F. Wugenig, *Tetrahedron: Asymmetry* **2003**, *14*, 1829–1836; f) V. Gouverneur, M.-N. Lalloz, *Tetrahedron Lett.* **1996**, *37*, 6331–6334.
- [3] a) P. G. Baraldi, M. Guarneri, F. Moroder, G. P. Pollini, D. Simoni, *Synthesis* **1982**, 653–655; b) T. Gajda, *Tetrahedron: Asymmetry* **1994**, *5*, 1965–1972; c) F. Hammerschmidt, F. Wugenig, *Tetrahedron: Asymmetry* **1999**, *10*, 1709–1721; d) T. Yokomatsu, Y. Yoshida, S. Shibuya, *J. Org. Chem.* **1994**, *59*, 7930–7933.
- [4] a) O. I. Kolodiaznyy, *Tetrahedron: Asymmetry* **2005**, *16*, 3295–3340; b) H. Gröger, B. Hammer, *Chem. Eur. J.* **2000**, *6*, 943–948; c) D. F. Wiemer, *Tetrahedron* **1997**, *53*, 16609–16644.
- [5] a) P. Merino, E. Marqués-López, R. P. Herrera, *Adv. Synth. Catal.* **2008**, *350*, 1195–1208; b) A. A. Smaardijk, S. Noorda, F. van Bolhuis, H. Wynberg, *Tetrahedron Lett.* **1985**, *26*, 493–496; c) T. Yamagishi, T. Yokomatsu, K. Suemune, S. Shibuya, *Tetrahedron* **1999**, *55*, 12125–12136; d) B. J. Rowe, C. D. Spilling, *Tetrahedron: Asymmetry* **2001**, *12*, 1701–1708; e) M. Shibasaki, H. Sasai, T. Arai, *Angew. Chem. Int. Ed. Engl.* **1997**, *36*, 1236–1256; f) C. V. Ward, M. Jiang, T. P. Kee, *Tetrahedron Lett.* **2000**, *41*, 6181–6184; g) B. Saito, H. Egami, T. Katsuki, *J. Am. Chem. Soc.* **2007**, *129*, 1978–1986; h) X. Zhou, X. Liu, X. Yang, D. Shang, J. Xin, X. Feng, *Angew. Chem. Int. Ed.* **2008**, *47*, 392–394; i) S. Gou, X. Zhou, J. Wang, X. Liu, X. Feng, *Tetrahedron* **2008**, *64*, 2864–2870; j) F. Yang, D. Zhao, J. Lan, P. Xi, L. Yang, S. Xiang, J. You, *Angew. Chem. Int. Ed.* **2008**, *47*, 5646–5649.
- [6] The first example of the catalytic asymmetric Abramov-type phosphorylation of aldehydes with trialkyl phosphites was reported while the present publication was in preparation, see: K. Nakanishi, S. Kotani, M. Sugiura, M. Nakajima, *Tetrahedron* **2008**, *64*, 6415–6419.

- [7] a) C. Meier, W. H. G. Laux, J. W. Bats, *Liebigs Ann.* **1995**, 1963–1979; b) C. Meier, W. H. G. Laux, *Tetrahedron: Asymmetry* **1995**, 6, 1089–1092; c) C. Meier, W. H. G. Laux, *Tetrahedron* **1996**, 52, 589–598; d) A. Barco, S. Benetti, P. Bergamini, C. De Risi, P. Marchetti, G. P. Pollini, V. Zanirato, *Tetrahedron Lett.* **1999**, 40, 7705–7708.
- [8] a) M. Kitamura, M. Tokunaga, R. Noyori, *J. Am. Chem. Soc.* **1995**, 117, 2931–2932; b) M. Kitamura, M. Tokunaga, T. Pham, W. D. Lubell, R. Noyori, *Tetrahedron Lett.* **1995**, 36, 5769–5772; c) I. Gautier, V. Ratovelomanana-Vidal, P. Savignac, J.-P. Genêt, *Tetrahedron Lett.* **1996**, 37, 7721–7724.
- [9] W. Tang, X. Zhang, *Chem. Rev.* **2003**, 103, 3029–3069.
- [10] a) G. P. Chiusoli, G. Cometti, V. Bellotti, *Gazz. Chim. Ital.* **1977**, 107, 217–222; b) H. Nakazawa, Y. Matsuoka, I. Nakagawa, K. Miyoshi, *Organometallics* **1992**, 11, 1385–1392.
- [11] a) M. J. Burk, T. A. Stammers, J. A. Straub, *Org. Lett.* **1999**, 1, 387–390; b) I. D. Gridnev, M. Yasutake, T. Imamoto, I. P. Beletskaya, *Proc. Natl. Acad. Sci. USA* **2004**, 101, 5385–5390; c) T. Imamoto, K. Yashio, K. V. L. Crêpy, K. Katagiri, H. Takahashi, M. Kouchi, I. D. Gridnev, *Organometallics* **2006**, 25, 908–914; d) M. Rubio, A. Suárez, E. Álvarez, A. Pizzano, *Chem. Commun.* **2005**, 628–630; e) M. Rubio, S. Vargas, A. Suárez, E. Álvarez, A. Pizzano, *Chem. Eur. J.* **2007**, 13, 1821–1833; f) D.-Y. Wang, X.-P. Hu, J.-D. Huang, J. Deng, S.-B. Yu, Z.-C. Duan, X.-F. Xu, Z. Zheng, *Angew. Chem. Int. Ed.* **2007**, 46, 7810–7813; g) D.-Y. Wang, J.-D. Huang, X.-P. Hu, J. Deng, S.-B. Yu, Z.-C. Duan, Z. Zheng, *J. Org. Chem.* **2008**, 73, 2011–2014; h) H. Liu, Y.-G. Zhou, Z.-K. Yu, W.-J. Xiao, S.-H. Liu, H.-W. He, *Tetrahedron* **2006**, 62, 11207–11217.
- [12] a) N. S. Goulioukina, G. N. Bondarenko, S. E. Lyubimov, V. A. Davankov, K. N. Gavrilov, I. P. Beletskaya, *Adv. Synth. Catal.* **2008**, 350, 482–492; b) for example, when diethyl benzoylphosphonate (**1a**) was tested under the optimal conditions found for the hydrogenation of α -imino phosphonates {MeOH, 10 bar H_2 , 60 °C, [Rh(Cod) $_2$] $^+$ SbF $_6^-$ /(*R*)-BINAP (3 mol-%), 6 h} complete conversion was observed, but the yield of the desired diethyl [hydroxy(phenyl)methyl]phosphonate (**2a**) was 12% with diethyl phosphite arising as the main product (74%).
- [13] N. S. Gulyukina, G. N. Bondarenko, A. D. Averin, V. I. Isaeva, E. D. Finashina, L. M. Kustov, I. P. Beletskaya, *Russ. J. Org. Chem. (Engl. Trans.)* **2007**, 43, 1180–1185.
- [14] L. F. Tietze, H. Ila, H. P. Bell, *Chem. Rev.* **2004**, 104, 3453–3516.
- [15] a) H. Abe, H. Amii, K. Uneyama, *Org. Lett.* **2001**, 3, 313–315; b) A. Suzuki, M. Mae, H. Amii, K. Uneyama, *J. Org. Chem.* **2004**, 69, 5132–5134; c) Q. Yang, G. Shang, W. Gao, J. Deng, X. Zhang, *Angew. Chem. Int. Ed.* **2006**, 45, 3832–3835; d) Y.-Q. Wang, S.-M. Lu, Y.-G. Zhou, *J. Org. Chem.* **2007**, 72, 3729–3734.
- [16] Y.-Q. Wang, S.-M. Lu, Y.-G. Zhou, *Org. Lett.* **2005**, 7, 3235–3238.
- [17] X.-X. Guo, J.-H. Xie, G.-H. Hou, W.-J. Shi, L.-X. Wang, Q.-L. Zhou, *Tetrahedron: Asymmetry* **2004**, 15, 2231–2234.
- [18] a) K. N. Gavrilov, S. E. Lyubimov, S. V. Zheglov, E. B. Benetsky, P. V. Petrovskii, E. A. Rastorguev, T. B. Grishina, V. A. Davankov, *Adv. Synth. Catal.* **2007**, 349, 1085–1094; b) K. N. Gavrilov, S. E. Lyubimov, S. V. Zheglov, E. B. Benetsky, V. A. Davankov, *J. Mol. Catal. A* **2005**, 231, 255–260; c) V. N. Tsarev, S. E. Lyubimov, O. G. Bondarev, A. A. Korlyukov, M. Yu. Antipin, P. V. Petrovskii, V. A. Davankov, A. A. Shiryaev, E. B. Benetsky, P. A. Vologzhanin, K. N. Gavrilov, *Eur. J. Org. Chem.* **2005**, 2097–2105; d) K. N. Gavrilov, S. V. Zheglov, P. A. Vologzhanin, M. G. Maksimova, A. S. Safronov, S. E. Lyubimov, V. A. Davankov, B. Schöffner, A. Börner, *Tetrahedron Lett.* **2008**, 49, 3120–3123; e) A. A. Kabro, S. E. Lyubimov, M. G. Maksimova, S. K. Moiseev, K. N. Gavrilov, V. N. Kalinin, *Russ. Chem. Bull. (Engl. Trans.)* **2007**, 56, 540–542.
- [19] I. A. Shuklov, N. V. Dubrovina, A. Börner, *Synthesis* **2007**, 2925–2943.
- [20] In the 1H NMR spectra of the crude reaction mixtures, besides the signals from **1b** (δ_P = –2.1 ppm) and **2b** (δ_P = 20.5 ppm) other low-intensity signals were detected: a singlet of diisopropyl phosphite at δ_P = 5.2 ppm, a singlet at δ_P = –2.8 ppm and a couple of doublets of equal intensity at δ_P = –2.1 (J_{PP} = 39.6 Hz) and 15.9 ppm (J_{PP} = 39.6 Hz).
- [21] Y.-F. Li, F. Hammerschmidt, *Tetrahedron: Asymmetry* **1993**, 4, 109–120.
- [22] C. Meier, W. H. G. Laux, *Tetrahedron: Asymmetry* **1996**, 7, 89–94.
- [23] a) K. Błażewska, T. Gajda, *Tetrahedron: Asymmetry* **2002**, 13, 671–674; b) K. Błażewska, P. Paneth, T. Gajda, *J. Org. Chem.* **2007**, 72, 878–887.
- [24] A. H. Ford-Moore, B. J. Perry *Org. Synth.* **1963**, Coll. Vol. 4, 955–957.
- [25] K. Nagasawa, S. Yoshitake, T. Amiya, K. Ito, *Synth. Commun.* **1990**, 20, 2033–2040.
- [26] T. A. Stephenson, S. M. Morehouse, A. R. Powell, J. P. Heffer, G. Wilkinson, *J. Chem. Soc.* **1965**, 3632–3640.
- [27] A. M. d'A. R. Gonsalves, M. E. S. Serra, D. Murtinho, V. F. Silva, A. M. Beja, J. A. Paixão, M. R. Silva, L. A. da Veiga, *J. Mol. Catal. A* **2003**, 195, 1–9.
- [28] V. N. Tsarev, S. E. Lyubimov, A. A. Shiryaev, S. V. Zheglov, O. G. Bondarev, V. A. Davankov, A. A. Kabro, S. K. Moiseev, V. N. Kalinin, K. N. Gavrilov, *Eur. J. Org. Chem.* **2004**, 2214–2222.
- [29] a) K. D. Berlin, R. T. Claunch, E. T. Gaudy, *J. Org. Chem.* **1968**, 33, 3090–3095; b) K. D. Berlin, H. A. Taylor, *J. Am. Chem. Soc.* **1964**, 86, 3862–3866; c) A. Tromelin, D. El Manouni, R. Burgada, *Phosphorus Sulfur* **1986**, 27, 301–312; d) R. I. Jurtschenko, T. I. Klepa, W. F. Baklan, N. A. Fokina, A. A. Kudrjawchew, W. P. Kukhar, *Zhur. Obshch. Khim. (Russian)* **1992**, 62, 1760–1764; e) P. A. Turhanen, M. J. Ahlgren, T. Järvinen, J. J. Vepsäläinen, *Phosphorus Sulfur Silicon Relat. Elem.* **2001**, 170, 115–133.
- [30] a) F. Texier-Boullet, A. Foucaud, *Synthesis* **1982**, 916; b) W. Goldman, M. Soroka, *Synthesis* **2006**, 3019–3024.
- [31] V. S. Abramov, A. L. Shalman, A. P. Bulgakova in *Chemistry of Organophosphorus Compounds (Russian)*, Nauka, Leningrad, **1967**, pp. 132–135.
- [32] V. S. Abramov, Sh. Pall, *Zhur. Obshch. Khim. (Russian)* **1957**, 27, 172.
- [33] G. Eidenhammer, F. Hammerschmidt, *Synthesis* **1996**, 748–754.

Received: September 26, 2008

Published Online: December 18, 2008