Enantioselective 1,4-Addition of Ar_3Bi, $[ArBF_3]K$, and $ArSiF_3$ to Enones Catalyzed by a Dicationic Palladium(II)−Chiraphos or −Dipamp Complex

Takashi Nishikata,[†] Yasunori Yamamoto,[‡] Ilya D. Gridnev,[§] and Norio Miyaura*,[‡]

Innovation Plaza Hokkaido, Japan Science and Technology Agency, Sapporo 060-0819, Japan, Division of Chemical Process Engineering, Graduate School of Engineering, Hokkaido University, Sapporo 060-8628, Japan, and COE Laboratory, Department of Chemistry, Graduate School of Science, Tohoku University, Sendai 980-8578, Japan

Received August 4, 2005

Chiral complexes of $[Pd(S,S\text{-chiraphos})(PhCN)_2](SbF_6)_2$ (**2b**) and $[Pd(S,S\text{-dipamp})(PhCN)_2](SbF_6)_2$ (**2c**) catalyzed the highly enantioselective 1,4-additions of Ar_3Bi, $[ArBF_3]K$, and $ArSiF_3$ to cyclic and acyclic enones in aqueous methanol. The complexes catalyzed the reactions of Ar_3Bi and $ArSiF_3$ at 0−5 °C in the presence of $Cu(BF_4)_2$ or ZnF_2, whereas they smoothly prompted the addition of $[ArBF_3]K$ at −15 °C without further activation of the catalysts. The highest enantioselectivities giving β-aryl ketones up to 99% ee were attained when using **2b** for 2-cyclopentenone and acyclic (*E*)-enones, whereas **2c** resulted in the best selectivities for 2-cyclohexenone and 2-cycloheptenone (89−96% ee). The effects on enantioselection of chiral ligands and substituents on α,β-unsaturated ketones are discussed on the basis of X-ray structures of **2b** and **2c** as well as DFT computational studies on mechanistic aspects of the catalytic cycle.

Introduction

Conjugate additions of organometallic reagents to electrophilically activated alkenes are one of the versatile methodologies for forming carbon−carbon bonds. Since the reaction yields β-substituted carbonyl compounds that are of great value as synthetic intermediates, considerable efforts have been devoted to the development of asymmetric syntheses.[1] In studies on asymmetric carbon−carbon bond formation, metal catalysts have been exhibited a significantly higher degree of enantioselectivity and generality with respect to reactants or substrates. A variety of enantioselective Michael additions of keto esters or their analogues were developed by the metal−binol catalysts of Shibasaki,[2] the dicationic palladium(II)−binap catalysts of Sodeoka,[3] the ruthenium−diamine−arene catalysts of Ikariya,[4] and the salen−aluminum catalysts of Jacobsen.[5] In studies on 1,4-addition of organometallic reagents, the most commonly used catalyst is copper, such as copper−phosphoramidite catalysts developed by Feringa, in combination with organomagnesium or -zinc compounds.[6] The corresponding reactions of rhodium catalysts[7] succeeded in addition of nonmetallic reagents of organoboron[8] and -silicon[9] as well as metallic com-

[†] Japan Science and Technology Agency.
[‡] Hokkaido University.
[§] Tohoku University.

(1) (a) Krause, N.; Hoffmann-Röder, A. *Synthesis* **2001**, 171. (b) Sibi, M. P.; Manyem, S. *Tetrahedron* **2000**, *56*, 8033. (c) Tomioka, K.; Nagaoka, Y. In *Comprehensive Asymmetric Catalysis*; Jacobsen, E. N., Pfalts, A., Yamamoto, H., Eds.; Springer-Verlag: Berlin, 1999; Chapter 31.1.

(2) (a) Sasai, H.; Arai, T.; Satow, Y.; Houk, K. N.; Shibasaki, M. *J. Am. Chem. Soc*. **1995**, *117*, 6194. (b) Sasai, H.; Emori, E.; Arai, T.; Shibasaki, M. *Tetrahedron Lett*. **1996**, *37*, 5561. (c) Arai, T.; Sasai, H.; Aoe, K.; Okamura, K.; Date, T.; Shibasaki, M. *Angew. Chem., Int. Ed*. **1996**, *35*, 104. (d) Majima, K.; Takita, R.; Okada, A.; Ohshima, T.; Shibasaki, M. *J. Am. Chem. Soc*. **2003**, *125*, 15837.

(3) (a) Hamashima, Y.; Hotta, D.; Sodeoka, M. *J. Am. Chem. Soc*. **2002**, *124*, 11240. (b) Hamashima, Y.; Sodeoka, M. *Chem. Rec*. **2004**, *4*, 231. A rhodium-catalyzed reaction has also been reported: Suzuki, T.; Torii, T. *Tetrahedron: Asymmetry* **2001**, *12*, 1077.

(4) (a) Watanabe, M.; Murata, K.; Ikariya, T. *J. Am. Chem. Soc*. **2003**, *125*, 7508. (b) Watanabe, M.; Ikagawa, A.; Wang,, H.; Murata, K.; Ikariya, T. *J. Am. Chem. Soc*. **2004**, *126*, 11148. (c) Wang, H.; Watanabe, M.; Ikariya, T. *Tetrahedron Lett*. **2005**, *46*, 963.

(5) Taylor, M. S.; Zalatan, D. N.; Lerchner, A. M.; Jacobsen, E. N. *J. Am. Chem. Soc*. **2005**, *127*, 1313.

(6) (a) Feringa, B. L.; Pineschi, M.; Arnold, L. A.; Imbos, R.; De Vries, A. M. H.; *Angew. Chem., Int. Ed*. **1997**, *36*, 2620. (b) Duursma, A.; Minnaard, A. J.; Feringa, B. L. *J. Am. Chem. Soc*. **2003**, *125*, 3700. (c) Šebesta, R.; Pizzuti, M. G.; Boersma, A. J.; Minnaard, A. J.; Feringa, B. L. *Chem. Commun*. **2005**, 1711.

(7) Sakai, M.; Hayashi, H.; Miyaura, N. *Organometallics* **1997**, *16*, 4229.

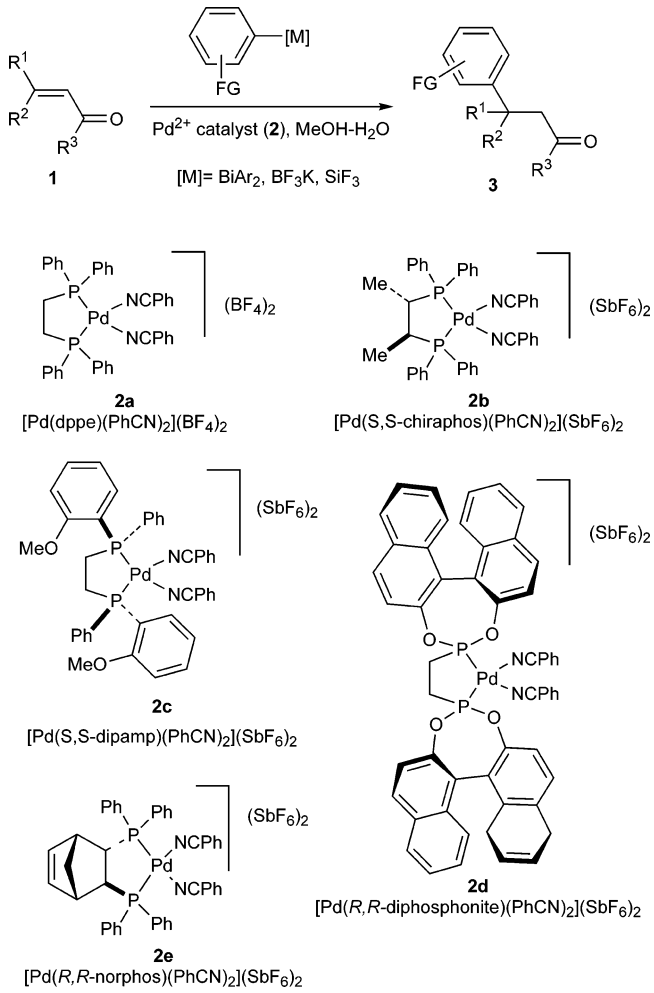
(8) (a) Takaya, Y.; Ogasawara, M.; Hayashi, T.; Sakai, M.; Miyaura, N. *J. Am. Chem. Soc.*, **1998**, *120*, 5579. (b) Batey, R. A.; Thadani, A. N.; Smil, D. V. *Org. Lett.* **1999**, *1*, 1683. (c) Hayashi, T.; Senda, T.; Takaya, Y.; Ogasawara, M. *J. Am. Chem. Soc.* **1999**, *121*, 11591. (d) Reetz, M. T.; Moulin, D.; Gosberg, A. *Org. Lett*. **2001**, *3*, 4083. (e) Ramnaulth, J.; Poulin, O.; Bratovanov, S. S.: Rakhit, S.; Maddaford, S. P. *Org. Lett*. **2001**, *3*, 2571. (f) Itooka, R.; Iguchi, Y.; Miyaura, N. *Chem. Lett*. **2001**, 722. (g) Yamamoto, Y.; Fujita, M.; Miyaura, N. *Synlett* **2002**, 767. (h) Amengual, R.; Michelet, V.; Genêt, J.-P. *Tetrahedron Lett*. **2002**, *43*, 5905. (i) Pucheault, M.; Darses, S.; Genêt, J.-P. *Tetrahedron Lett*. **2002**, *43*, 6155. (j) Hayashi, T.; Takahashi, M.; Takaya, Y.; Ogasawara, M. *J. Am. Chem. Soc*. **2002**, *124*, 5052. (k) Itooka, R.; Iguchi, Y.; Miyaura, N. *J. Org. Chem*., **2003**, *68*, 6000. (l) Ma, Y.; Song, C.; Ma, C.; Sun, Z.; Chai, Q.; Andrus, M. B. *Angew. Chem., Int. Ed*. **2003**, *42*, 5871. (m) Cauble, D. F.; Gipson, J. D.; Krische, M. J. *J. Am. Chem. Soc.* **2003**, *125*, 1110. (n) Navarre, L.; Pucheault, M.; Darses, S.; Genêt, J.-P. *Tetrahedron Lett*. **2005**, *46*, 4247. (o) Chen, G.; Tokunaga, N.; Hayashi, T. *Org. Lett*. **2005**, *7*, 2285. For a review, see: (p) Hayashi, T: Yamasaki, K. *Chem. Rev*. **2003**, *103*, 2829.

(9) (a) Mori, A.; Danda, Y.; Fujii, T.; Hirabayashi, K.; Osakada, K. *J. Am. Chem. Soc.* **2001**, *123*, 10774. (b) Huang, T.-S.; Li, C.-J. *Chem. Commun*. **2001**, 2348. (c) Oi, S.; Honma, Y.; Inoue, Y. *Org. Lett.* **2002**, *4*, 667. (d) Murata, M.; Shimazaki, R.; Ishikura, M.; Watanabe, S.; Masuda, Y. *Synthesis* **2002**, 717. (e) Koike, T.; Du, X.; Mori, A.; Osakada, K. *Synlett* **2002**, 301. (f) Oi, S.; Taira, A.; Honma, Y.; Inoue, Y. *Org. Lett*. **2003**, *5*, 97.

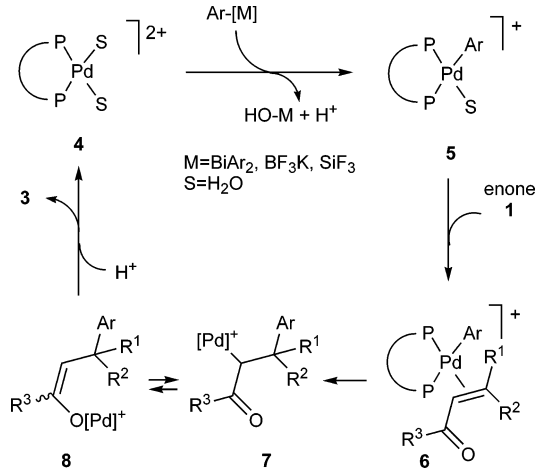
10.1021/om050678t CCC: $30.25 © 2005 American Chemical Society
Publication on Web 09/08/2005

pounds of organotitanium,[10] -zinc,[11] -tin,[12] and -bismuth.[13] The protocol is of synthetic value because of the availability of chiral ligands and a wide scope with respect to cyclic and acyclic α,β-unsaturated ketones,[8] esters,[8] amides,[14] phosphonates,[15] and nitro compounds.[16] The high stability of B, Si, Sn, and Bi compounds to air and moisture allows the reactions in aqueous media. An enantioselective reaction was first achieved by rhodium(I)−binap catalysts in 1,4-addition of aryl- and 1-alkenylboronic acids to cyclic and acyclic enones.[8a] Other ligands effective for rhodium(I) catalysts are bisphosphine ligands of chiraphos[17] and diphosphonites,[18] P−N ligands of amidomonophosphines,[19] bis(alkene) ligands based on a norbornadiene skeleton,[20] and monophosphine ligands of phosphoramidites.[21] The corresponding reactions of palladium(II) catalysts are rare, due to a marked tendency to yield Heck coupling products or to be reduced to palladium(0) complexes. We recently reported that dicationic palladium(II) complexes such as $[Pd(dppe)(S)_2]^{2+}$ efficiently catalyze 1,4-addition of $ArB(OH)_2$,[22] $[ArBF_3]K$,[23] $ArSi(OMe)_3$,[24] and Ar_3Bi[25] to enones via a transmetalation−insertion−hydrolysis sequence[26] analogous to the catalytic cycle of rhodium(I)-catalyzed reactions. Among them, two reactions of Ar_3Bi[25] and $[ArBF_3]K$[23] were recently extended to asymmetric versions (Scheme 1). In this paper, we report the scope and limitations of the protocol as well as the preparation and X-ray structures of chiral catalysts (**2**) that are effective at temperatures below 0 °C. Chiral ligands having a relatively large bite angle such as binap have been successfully used for rhodium-catalyzed reactions, but bisphosphines bridged by two carbons, such as chiraphos and dipamp, resulted in high yields and high enantioselectivities for palladium catalysts.

Scheme 1. 1,4-Addition of Ar_3Bi, $[ArBF_3]K$, and $ArSiF_3$ to Enones



Scheme 2. Proposed Catalytic Cycle



Results and Discussion

Catalytic Cycle. The catalytic cycle shown in Scheme 2[26] was proposed on the basis of isolation and X-ray characterization of the transmetalation intermediate (**5**) between $[Pd(dppe)(PhCN)_2](BF_4)_2$ (**2a**) and $PhB(OH)_2$. Addition of **5** to enone in an aqueous solvent gave a 1,4-addition product (**3**) via a sequence of insertion of an enone into the Ar−Pd bond of **5**, giving C- and O-bound enolates (**7** and **8**), and their hydrolysis with water. The

(10) Hayashi, T.; Tokunaga, N.; Yoshida, K.; Han, J. W. *J. Am. Chem. Soc*. **2002**, *124*, 12102.
(11) Shintani, R.; Tokunaga, N.; Doi, H.; Hayashi, T. *J. Am. Chem. Soc*. **2004**, *126*, 6240.
(12) (a) Oi, S.; Moro, M.; Ono, S.; Inoue, Y. *Chem. Lett*. **1998**, 83. (b) Huang, T.-S.; Li, C.-J. *Org. Lett*. **2001**, *3*, 2037. (c) Huang, T.; Meng, Y.; Venkatraman, S.; Wang, D.; Li, C.-J. *J. Am. Chem. Soc.* **2001**, *123*, 7451. (d) Oi, S.; Moro, M.; Ito, H.; Honma, Y.; Miyano, S.; Inoue, Y. *Tetrahedron* **2002**, *58*, 91.
(13) Venkatraman, S.; Li, C.-J. *Tetrahedron Lett*. **2001**, *42*, 781.
(14) (a) Sakuma, S.; Miyaura, N. *J. Org. Chem*. **2001**, *66*, 8944. (b) Pucheault, M.; Michaut, V.; Darses, S.; Genêt, J.-P. *Tetrahedron Lett*. **2004**, *45*, 4729.
(15) Hayashi, T.; Senda, T.; Takaya, Y.; Ogasawara, M. *J. Am. Chem. Soc*. **1999**, *121*, 11591.
(16) Hayashi, T.; Senda, T.; Ogasawara, M. *J. Am. Chem. Soc*. **2000**, *122*, 10716.
(17) Mauleon, P.; Carretero, J. C. *Org. Lett*. **2004**, *6*, 3195.
(18) Reetz, M. T.; Moulin, D.; Gosberg, A. *Org. Lett*. **2001**, *3*, 4083.
(19) (a) Kuriyama, M.; Tomioka, K. *Tetrahedron Lett*. **2001**, *42*, 921. (b) Kuriyama, M.; Nagai, K.; Yamada, K.; Miwa, Y.; Taga, T.; Tomioka, K. *J. Am. Chem. Soc*. **2002**, *124*, 8932.
(20) (a) Hayashi, T.; Ueyama, K.; Tokunaga, N.; Yoshida, K. *J. Am. Chem. Soc*. **2003**, *125*, 11508. (b) Shintani, R.; Ueyama, K.; Yamada, I.; Hayashi, T. *Org. Lett*. **2004**, *6*, 3425. (c) Defieber, C.; Paquin, J.-F.; Serna, S.; Carreira, E. M. *Org. Lett*. **2004**, *6*, 3873.
(21) (a) Iguchi, Y.; Itooka, R.; Miyaura, N. *Synlett* **2003**, 1040. (b) Duursma, A.; Hoen, R.; Schuppan, J.; Hulst, R.; Minnaard, A. J.; Feringa, B. L. *Org. Lett*. **2003**, *5*, 3111. (c) Boiteau, J.-G.; Minnaard, A. J.; Feringa, B. L. *J. Org. Chem*. **2003**, *68*, 9481.
(22) Nishikata, T.; Yamamoto, Y.; Miyaura, N. *Angew. Chem., Int. Ed*. **2003**, *42*, 2768.
(23) Nishikata, T.; Yamamoto, Y.; Miyaura, N. *Chem. Lett*. **2005**, *34*, 720.
(24) Nishikata, T.; Yamamoto, Y.; Miyaura, N. *Chem. Lett*. **2003**, *32*, 752.
(25) Nishikata, T.; Yamamoto, Y.; Miyaura, N. *Chem. Commun*. **2004**, 1822.
(26) Nishikata, T.; Yamamoto, Y.; Miyaura, N. *Organometallics* **2004**, 23, 4317.

cationic palladium(II) catalysts meet several requirements for developing a catalytic cycle of the 1,4-addition in aqueous media. (i) The transmetalation to palladium(II)−halogen complexes involved in palladium-catalyzed cross-coupling reactions of organoboron and silicon compounds requires the presence of bases,[27] but they smoothly react with dicationic palladium(II) complexes under neutral conditions; e.g., $PhB(OH)_2$ and $PhSi(OMe)_3$ transmetalate to **2a** at room temperature, giving **5**.[26,28] The in situ prepared nitrile-free complex **4** is a much more active catalyst than a bench-stable nitrile complex (**2a**). Hence, the dissociation of benzonitrile from **2a**, yielding the solvent-coordinated complex **4**, probably precedes the transmetalation. Such a high reactivity of cationic nitrile-free complexes has been previously reported in the stoichiometric reaction between $[Pt(S)_2(PEt_3)_2][CF_3SO_3]_2$ (S = MeOH, H_2O) and $[Ph_4B]Na$ or $PhB(OH)_2$, giving $[Pt(Ph)(S)(PEt_3)_2]^{2+}$.[29] (ii) The presence of a vacancy in the square-planar palladium(II) center (**5**) causes marked rate enhancement toward alkene insertion over those of neutral complexes, as has been demonstrated in the palladium-catalyzed Heck reaction,[30] the Mannich reaction,[31b] the aldol reaction,[31a] and the polymerization of alkenes.[32] The reactivity toward methyl acrylate increases in the order *trans*-$[Pd(Ph)(Br)(PMe_3)_2]$ < *trans*-$[Pd(Ph)(PMe_3)_2(pyridine)]BF_4$ < *trans*-$[Pd(Ph)(PMe_3)_2(solvent)]BF_4$, indicating involvement of one ligand dissociation before the coordination−insertion process.[30c,d] (iii) Unlike neutral palladium enolates, which generally give Heck products via β-hydride elimination, the cationic palladium(II) enolates (**7** and **8**) are highly susceptible to hydrolytic cleavage. The cationic palladium(II) enolate complexes exist in solution as equilibrating C-bound (**7**) and O-bound tautomers (**8**),[33] though they mostly take a C-bound structure (**7**) in the solid state.[34] The oxa-π-allyl coordination mode has been found in a cationic binap complex.[31a]

Reaction Conditions. The optimal solvent system for 1,4-additions of Ph_3Bi, $[PhBF_3]K$, and $PhSiF_3$ (1.5 equiv) to 2-cyclohexenone is MeOH−H_2O (Table 1). The reaction is catalyzed by dicationic palladium(II) complexes of dppe (**2a**) and dppben in high yields, but the corresponding dppm, dppp, dppb, dppf, binap. and PPh_3 complexes do not catalyze 1,4-addition of $ArB(OH)_2$, $ArSi(OMe)_3$, and Ar_3Bi to enones.[22−26] Thus, representative chiral bisphosphines bridged by two carbon atoms (**2b**−**e**) were screened for asymmetric catalysts.

Table 1. Reaction Conditions

entry	Ph−[M]	palladium cat./ additive (amt/equiv)[c]	temp/ °C	yield/ %[b]	% ee (confign)
1	Ph_3Bi	**2a**[d]	20	27[e]	
2	Ph_3Bi	**2a**[d]/$Cu(BF_4)_2$ (0.76)	20	90[e]	
3	Ph_3Bi	**2b**/$Cu(BF_4)_2$ (0.76)	−5	89	12 (*S*)
4	Ph_3Bi	**2c**/$Cu(BF_4)_2$ (0.76)	−5	92	92 (*R*)
5	Ph_3Bi	**2d**/$Cu(BF_4)_2$ (0.76)	20	trace	
6	Ph_3Bi	**2e**/$Cu(BF_4)_2$ (0.76)	20	trace	
7	$[PhBF_3]K$	**2a**[d]	−5	86	
8	$[PhBF_3]K$	**2a**[d]/$Cu(BF_4)_2$ (0.76)	−5	88	
9	$[PhBF_3]K$	**2c**	10	99	90 (*R*)
10	$[PhBF_3]K$	**2c**	−5	99	92 (*R*)
11	$[PhBF_3]K$	**2c**	−15	95	93 (*R*)
12	$[PhBF_3]K$	**2c**	−30	trace	
13	$[PhBF_3]K$	**2b**	−15	57	8 (*S*)
14	$PhB(OH)_2$	**2a**[d]	−5	21	
15	$PhB(OH)_2$	**2a**[d]/$BF_3{\cdot}OEt_2$ (1.0)	−5	74	
16	$PhSiF_3$	**2a**[d]	25	86	
17	$PhSiF_3$	**2a**[d]	0	50	
18	$PhSiF_3$	**2a**[d]/$Cu(BF_4)_2$ (0.37)	0	29	
19	$PhSiF_3$	**2a**[d]/ZnF_2 (1.0)	0	72	
20	$PhSiF_3$	**2c**/ZnF_2 (1.0)	0	83	92 (*R*)
21	$PhSiF_3$	**2b**/ZnF_2 (1.0)	0	80	9 (*S*)

[a] A mixture of 2-cyclohexenone (1 mmol) and Ph−[M] (1.5 mmol) in MeOH−H_2O (10/1 or 6/1, 6.6 mL) was stirred for 21 h in the presence of a palladium catalyst (**2**; 3 mol %) and an additive (if used). [b] Isolated yields by column chromatography. [c] Equivalents toward the enone. [d] 5 mol % of **2a** was used. [e] Biphenyl (18−24%) was also produced.

The benzonitrile complex (**2a**) is a bench-stable catalyst easily obtained from $PdCl_2$(dppe), PhCN, and $AgBF_4$,[35] but its use results in low yields accompanied by a substantial amount of biphenyl in 1,4-addition of Ph_3Bi at a temperature higher than 20 °C (Table 1, entry 1). The yield is improved to 90% in the presence of $Cu(BF_4)_2$ (0.76 equiv) (entry 2). Addition of $Cu(BF_4)_2$ is also highly effective for conducting the corresponding reactions of chiral catalysts (**2b**,**c**). The exact mechanism of biphenyl formation is not known, but it can be derived from double transmetalation of two phenyl groups to the palladium metal center, giving biphenyl and a catalytically inactive palladium(0) species via reductive elimination from a Ph−Pd−Ph intermediate. Thus, copper(II) salt is added to oxidize the palladium(0) species in order to regenerate the dicationic palladium(II) complex **4**. The formation of **4** via oxidation of $Pd(dba)_2$ with $Cu(BF_4)_2$ has been confirmed by ^{31}P NMR analysis (eq 1).[26] Another possible role of the copper salt is to facilitate ligand exchange between **2a** and $Cu(BF_4)_2$ in order to provide nitrile-free **4** (eq 2). Since both the transmetalation and insertion steps involve dissociation of one ligand from a square-planar four-coordinated complex,[30d] these complexes bearing a more weakly coordinating ligand (S = H_2O, solvent) react more quickly than those of nitrile complexes. In situ preparation of such nitrile-free catalysts from $PdCl_2$(dppe) and AgX (X = BF_4, SbF_6) is similarly effective at temperatures higher than 20 °C, but it is less effective at 0 °C (eq 3).

(27) (a) Miyaura, N.; Suzuki, A. *Chem. Rev*. **1995**, *95*, 2457. (b) Matos, K.; Soderquist, J. A. *J. Org. Chem*. **1998**, *63*, 461. (c) Miyaura, N. In *Metal-Catalyzed Cross-Coupling Reactions*, Meijere, A., Diederich, F., Eds.; Wiley-VCH: Weinheim, Germany, 2004; Vol. 1, pp 41−124.

(28) (a) Kang, S.-K.; Lee, H.-W.; Jang, S.-B.; Ho, P.-S. *J. Org. Chem*. **1996**, *61*, 4720. (b) Darses, S.; Genêt, J.-P.; Brayer, J.-L.; Demoute, J.-P. *Tetrahedron Lett*. **1997**, *38*, 4393. (c) Sengupta, S.; Bhattacharyya, S. *J. Org. Chem*. **1997**, *62*, 3405. (d) Wills, D. M.; Strongin, R. M. *Tetrahedron Lett*. **2000**, *41*, 6271. (e) Andrus, M. B.; Song, C. *Org. Lett*. **2001**, *3*, 3761. (f) Selvakumar, K.; Zapf, A.; Spannenberg, A.; Beller, M. *Chem. Eur. J*. **2002**, *8*, 3901.

(29) Siegmann, K.; Pregosin, P. S.; Venanzi, L. M. *Organometallics* **1989**, *8*, 2659.

(30) (a) Karabelas, K.; Westerlund, C.; Hallberg, A. *J. Org. Chem*. **1985**, 50, 3896. (b) Cabri, W.; Candiani, I.; Bedeschi, A.; Santi, R. *J. Org. Chem*. **1993**, 58, 7421. (c) Kawataka, F.; Shimizu, I.; Yamamoto, A. *Bull. Chem. Soc. Jpn*. **1995**, 68, 654. (d) Yamamoto, A. *J. Organomet. Chem*. **1995**, 500, 337.

(31) (a) Sodeoka, M.; Ohrai, K.; Shibasaki, M. *J. Org. Chem*. **1995**, *60*, 2648. (b) Fujii, A.; Hagiwara, E.; Sodeoka, M. *J. Am. Chem. Soc*. **1999**, *121*, 5450. (c) Sodeoka, M.; Hamashima Y. *Chem. Lett*. **2005**, 941 and references cited therein.

(32) (a) Johnson, L. K.; Killian, C. M.; Brookhart, M. *J. Am. Chem. Soc*. **1995**, *117*, 6414. (b) Liu, W.; Brookhart, M. *Organometallics* **2004**, *23*, 6099.

(33) Culkin, D. A.; Hartwig, J. F. *J. Am. Chem. Soc*. **2001**, *123*, 5816.

(34) (a) Albéniz, A. C.; Catalina, N. M.; Espinet, P.; Redón, R. *Organometallics* **1999**, *18*, 5571. (b) Veya, P.; Floriani, C.; Chiesi-Villa, A.; Rizzoli, C. *Organometallics* **1993**, *12*, 4899.

(35) (a) Davis, J. A.; Hartley, E. R.; Muray, S. G. *J. Chem. Soc., Dalton Trans*. **1980**, 2246. (b) Oi, S.; Kashiwagi, K.; Terada, E.; Ohuchi, K.; Inoue, Y. *Tetrahedron Lett*. **1996**, *37*, 6351.

$$Pd(dba)_2 + dppe + Cu(BF_4)_2 \longrightarrow \mathbf{4} \quad (1)$$

$$[Pd(dppe)(PhCN)_2]^{2+}\ (\mathbf{2a}) + Cu^{2+} \longrightarrow \mathbf{4} + [Cu(PhCN)_2]^{2+} \quad (2)$$

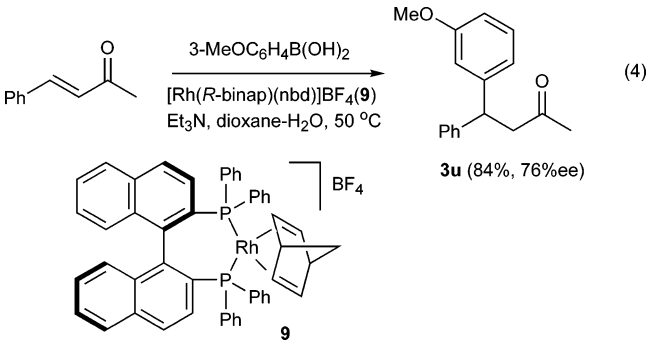
$$PdCl_2(dppe) + 2AgX \longrightarrow \mathbf{4} \quad (3)$$

The 1,4-addition reaction of $[PhBF_3]K$ is catalyzed by benzonitrile complexes of dppe, chiraphos, and dipamp (**2a**−**c**) (Table 1, entries 7−13). It is interesting that the reaction proceeded smoothly even at −15 °C without any activators such as $Cu(BF_4)_2$. Since transmetalation between **2a** and $[PhBF_3]K$ yields [Pd(Ph)(PhCN)(dppe)]-BF_4, KBF_4, PhCN, and BF_3, it is reasonable to assume that BF_3 thus generated traps benzonitrile, as does $Cu(BF_4)_2$. Indeed, the reaction of phenylboronic acid takes place at −5 °C in the presence of $BF_3{\cdot}OEt_2$ (entries 14 and 15). Although $[ArBF_3]K$, which is insoluble in common organic solvents, is used as a suspension in aqueous MeOH, it is a better reagent than arylboronic acids or esters.

The use of nitrile-free catalysts is also critical for arylsilicon compounds, because of their slow transmetalation compared to that of bismuth and boron compounds (Table 1, entries 16−22). $ArSi(OR)_3$[36] and $ArSiF_3$[9,37] are excellent reagents that have been successfully employed for metal-catalyzed C−C bond-forming reactions involving a transmetalation to palladium(II), nickel(II), or rhodium(I) complex. Although $ArSi(OMe)_3$ is added to enones at 75 °C by a nitrile-free catalyst in situ generated by the method of eq 1, all attempts to find a catalyst that is effective at low temperatures failed. Nevertheless, the reaction of $PhSiF_3$ can be carried out at 0 °C (entries 18−21). Addition of $Cu(BF_4)_2$ or $BF_3{\cdot}OEt_2$ is not effective (entries 16−18), but ZnF_2 (1.0 equiv) significantly accelerates the reaction (entries 19−21).

The 1,4-addition of Ph−[M] (M = $BiPh_2$, BF_3K, SiF_3) to 2-cyclohexenone with an *S,S*-dipamp catalyst (**2c**) provides (*R*)-3-phenylcyclohexanone with enantioselectivities in the range of 92−93%. The selectivity is slightly increased by decreasing the reaction temperature (Table 1, entries 9−11), but there are no notable differences between these three reagents when reactions are conducted at temperatures lower than 0 °C (entries 4, 11, and 20). The complex of *S,S*-chiraphos (**2b**) results in the formation of an opposite enantiomer (*S*) with significantly low selectivities (8−12% ee) (entries 3, 13 and 21), though it is an excellent catalyst for 2-cyclopentenone and acyclic enones as discussed in a later section. Other complexes prepared from analogous bisphosphines bridged by two carbon atoms have no catalytic activity even at room temperature. The reaction fails with Reetz's diphosphonite based on two 1,1′-binaphthols (**2d**) (entry 5).[8d] The norphos complex **2e** does not catalyze the reaction, due to its large bite angle compared to that of a dppe ligand (entry 6). The use of a complex of MeDuphos prepared in situ by the method of eq 2 also results in no reaction, due to the strong σ-donating ability of alkylphosphines.

Asymmetric Additions to Enones. Results of asymmetric 1,4-additions of the three reagents to representative cyclic and acyclic enones are shown in Table 2. Two catalysts of (*S,S*)-chiraphos (**2b**) and (*S,S*)-dipamp (**2c**) are employed at −5 to +10 °C in the presence of $Cu(BF_4)_2$ for Ar_3Bi (fifth column), at −15 to +0 °C without using any activators for $[ArBF_3]K$ (sixth column), and at 0 to +5 °C in the presence of ZnF_2 (1.0 equiv) for $ArSiF_3$ (seventh column). The highest enantioselectivities are attained when using **2b** for 2-cyclopentenone (entries 1−3) and acyclic (*E*)-enones (entries 13−24), whereas the use of **2c** results in the best selectivities for 2-cyclohexenone (entries 4−11) and 2-cyclopentenone (entry 12). There are no notable difference in enantioselectivities among these three reagents, though the reaction temperatures are varied from −15 to +10 °C. For example, the differences are within 2% ee in a series of additions of 3-methoxyphenyl derivatives of bismuth, boron, and silicon compound to 2-cyclohexenone at temperatures ranging from −15 to +10 °C (entry 6). However, 2-cycloheptenone, which has conformational flexibility, gives higher selectivity at lower temperature (entry 12). The enantioselectivities are affected by para or meta substituents on aryl reagents (wntries 4−11). Use of reagents possessing a meta substituent always results in selectivities higher than those of corresponding para-substituted compounds for both cyclic (entries 4−11) and acyclic enones (entries 18 and 19). This effect can be attributable to steric reasons, because it is independent of electronic properties of the substituents. The steric effect of the substituents R^1 and R^3 in acyclic enones (**1**) plays a key role in control of enantioselectivities (entries 13−24). In a series of enones possessing a primary pentyl group in R^1, the selectivities increased by increasing the bulkiness of R^3: e.g., CH_3 (80−83% ee) < n-C_4H_9 (85% ee) < $(CH_3)_2CH$ (87% ee) < cyclo-C_6H_{11} (87% ee) < Ph (88−89% ee) (entries 13−17). The effect of R^1 is much more significant for a series of methyl enones (R^3 = Me), n-C_5H_{11} (80−83% ee) < $(CH_3)_2CH$ (83−85% ee) < Ph (95% ee) (entries 13, 18, and 21). Among these representative enones, exceptionally high enantioselectivities of β-arylenones are characteristic for a chiraphos ligand (entries 21−24). The most selective catalysts for acyclic enones are rhodium−binap catalysts, which resulted in 83−98% ee for acyclic β-alkylenones.[8k] However, they are less effective for β-aryl enones. For example, a cationic Rh(I)−binap catalyst (**9**) results in 76% ee in the reaction of 3-methoxyphenylboronic acids with 4-phenyl-3-buten-2-one (eq 4).



(4)

Addition of $[PhBF_3]K$ to either cyclic or acyclic enones results in a different order and opposite sense of enantioselection in the presence of chiraphos- and

(36) (a) Shibata, K.; Miyazawa, K.; Goto, Y. *Chem. Commun*. **1997**, 1309. (b) Lee, J.-Y.; Fu, G. C. *J. Am. Chem. Soc*. **2003**, *125*, 5616. (c) Denmark, S. E.; Amishiro, N. *J. Org. Chem*. **2003**, *68*, 6997.

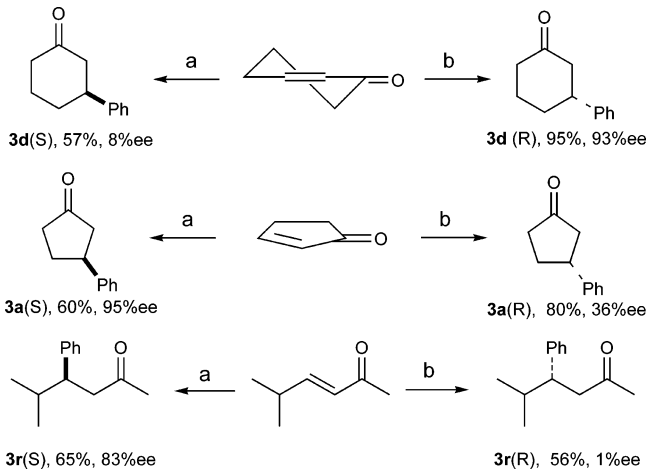
(37) (a) Matsuhashi, H.; Asai, S.; Hirabayashi, K.; Hatanaka, Y.; Mori, A.; Hiyama, T. *Bull. Chem. Soc. Jpn*. **1997**, *70*, 1943. (b) Powell, D. A.; Fu, G. C. *J. Am. Chem. Soc*. **2004**, *126*, 7788.

Table 2. Asymmetric 1,4-Addition of Ar_3Bi, $[ArBF_3]K$, and $ArSiF_3$ to Enones

					yield/%[a] (% ee)		
entry	Ar of Ar−[M]	enone	cat.	product	Ar_3Bi[b]	$[ArBF_3]K$[c]	$ArSiF_3$[d]
1	Ph	2-cyclopentenone	**2b**	**3a** (*S*)	85 (95)[h]	60 (95)[h]	83 (94)[g]
2	3-$MeOC_6H_4$	2-cyclopentenone	**2b**	**3b**	84 (92)[f]		
3	3-MeC_6H_4	2-cyclopentenone	**2b**	**3c**	94 (92)[h]		
4	Ph	2-cyclohexenone	**2c**	**3d** (*R*)	92 (92)[h]	95 (93)[i]	83 (92)[g]
5	4-$MeOC_6H_4$	2-cyclohexenone	**2c**	**3e**		89 (85)[h]	
6	3-$MeOC_6H_4$	2-cyclohexenone	**2c**	**3f**	92 (93)[e]	97 (95)[i]	99 (94)[f]
7	4-MeC_6H_4	2-cyclohexenone	**2c**	**3g**	64 (74)[h]	70 (90)[h]	
8	3-MeC_6H_4	2-cyclohexenone	**2c**	**3h**	98 (92)[h]	98 (93)[h]	
9	4-FC_6H_4	2-cyclohexenone	**2c**	**3i**	93 (90)[e]	99 (92)[h]	
10	3-FC_6H_4	2-cyclohexenone	**2c**	**3j**	93 (94)[e]	81 (96)[i]	81 (95)[g]
11	4-$CF_3C_6H_4$	2-cyclohexenone	**2c**	**3k**	66 (84)[e]	33 (87)[h]	
12	Ph	2-cycloheptenone	**2c**	**3l**	89 (76)[h]	91 (89)[i]	76 (76)[g]
13	Ph	(*E*)-*n*-$C_5H_{11}CH{=}CHCOCH_3$	**2b**	**3m**	99 (83)[h]	93 (82)[i]	80 (80)[g]
14	Ph	(*E*)-*n*-$C_5H_{11}CH{=}CHCO$*n*-C_4H_9	**2b**	**3n**			96 (85)[g]
15	Ph	(*E*)-*n*-$C_5H_{11}CH{=}CHCOCH(CH_3)_2$	**2b**	**3o**		93 (87)[i]	
16	Ph	(*E*)-*n*-$C_5H_{11}CH{=}CHCO$*c*-C_6H_{11}	**2b**	**3p**		98 (88)[i]	
17	Ph	(*E*)-*n*-$C_5H_{11}CH{=}CHCOPh$	**2b**	**3q**		99 (89)[i]	86 (88)[g]
18	Ph	(*E*)-$(CH_3)_2CHCH{=}CHCOCH_3$	**2b**	**3r** (*S*)	63 (85)[h]	65 (83)[h]	43 (83)[g]
19	3-$MeOC_6H_4$	(*E*)-$(CH_3)_2CHCH{=}CHCOCH_3$	**2b**	**3s**	70 (89)[e]		
20	Ph	(*E*)-c-$C_6H_{11}CH{=}CHCOCH_3$	**2b**	**3t**		22 (78)[h]	trace
21	3-$MeOC_6H_4$	(*E*)-$PhCH{=}CHCOCH_3$	**2b**	**3u**		90 (95)[g]	85 (95)[f]
22	3-$MeOC_6H_4$	(*E*)-$PhCH{=}CHCO$*n*-C_4H_9	**2b**	**3x**		91 (99)[f]	73 (99)[f]
23	3-$MeOC_6H_4$	(*E*)-$PhCH{=}CHCOPh$	**2b**	**3y** (*S*)		94 (97)[h]	88 (97)[f]
24	3-$MeOC_6H_4$	(*E*)-2-naphthylCH=CHCOCH$_3$	**2b**	**3z**		73 (96)[g]	66 (97)[f]

[a] Isolated yields by chromatography. [b] A mixture of enone (1 mmol), Ar_3Bi (0.6 mmol), Pd(2+) catalyst (**2**; 4 mol %), and $Cu(BF_4)_2{\cdot}6H_2O$ (0.76 mmol) in MeOH−H_2O (6/1) was stirred for 21 h. [c] A mixture of enone (1 mmol), $[ArBF_3]K$ (1.5 mmol), and Pd(2+) catalyst (**2**; 3 mol %) in MeOH−H_2O (10/1) was stirred for 21 h. [d] A mixture of enone (1 mmol), $ArSiF_3$ (2 mmol), Pd(2+) catalyst (**2**; 3 mol %), and ZnF_2 (1 mmol) in MeOH−H_2O (10/1) was stirred for 21 h. [e] At 10 °C. [f] At 5 °C. [g] At 0 °C. [h] At −5 °C. [i] At −15 °C.

Scheme 3. Enantioselection of *S,S*-Dipamp (2c) and *S,S*-Chiraphos (2b) Complex[a]



[a] Legend: (a) $[PhBF_3]K$ and **2b** in MeOH−H_2O; (b) $[PhBF_3]K$ and **2c** in MeOH−H_2O.

dipamp-based catalysts (Scheme 3). An *S,S*-chiraphos catalyst (**2b**) provides *S* products (**3a** and **3r**) with high enantioselectivities for 2-cyclopentenone and 5-methyl-3-hexen-2-one, respectively. Cyclohexenone, which results in 8% ee, again provides an *S* product (**3d**) by the same sense of enantioselection. On the other hand, an *S,S*-dipamp catalyst (**2c**) affords an excess of corresponding *R* enantiomers for three enones (**3a**,[38] **3d**,[39] **3r**[40]). Moreover, high ee (93%) was obtained only in the reaction with 2-cyclohexenone. A comparison of the structures of the three enones in Scheme 3 suggests that the most important feature for the catalyst−substrate recognition is the planarity of the substrate. Thus, both 2-cyclopentenone and 5-methyl-3-hexen-2-one, which have planar conformations, give high ee's in reactions catalyzed by **2b**. High enantioselectivities obtained for β-aryl ketones with **2b** can also be attributed to the planarity of aromatic rings. The formation of an *S* product in the reaction between (*E*)-PhCH=CHCOPh and $[3\text{-}MeOC_6H_4BF_3]K$ was confirmed by the X-ray analysis of **3y** (Table 2, entry 23). On the other hand, the skewed conformations of 2-cyclohexenone and 2-cycloheptenone require a dipamp ligand for achieving high orders of enantioselection.

Structural Studies of Palladium Complexes. The mechanisms of enantioselection in the asymmetric hydrogenation of prochiral alkenes catalyzed by rhodium[42] or iridium[43] complexes of chiraphos and dipamp have been actively studied.[44] In the asymmetric hydrogenation of enamides, enantioselection occurs via chelating coordination of the C−C double bond and the carbonyl oxygen to the rhodium(I) or iridium(I) metal center. However, there is little information on monoco-

(38) (*S*)-3-Phenylcyclopentanone (44% ee): $[\alpha]_D = -67.7°$ ($c = 0.1$, $CHCl_3$). Barnhart, R. W.; Wang,; X.; Noheda, P.; Bergens, S. H.; Whelan, J.; Bosnich, B. *J. Am. Chem. Soc.* **1994**, *116*, 1821.

(39) (*R*)-3-Phenylcyclohexanone (98.7% ee): $[\alpha]_D = +20.5°$ ($c = 0.58$, $CHCl_3$). Schultz, A. G.; Harrington, R. E. *J. Am. Chem. Soc.* **1991**, *113*, 4926.

(40) (*S*)-5-Methyl-3-phenyl-2-hexanone (97% ee): $[\alpha]_D = -33°$ ($c = 1.12$, $CHCl_3$).[8a,11]

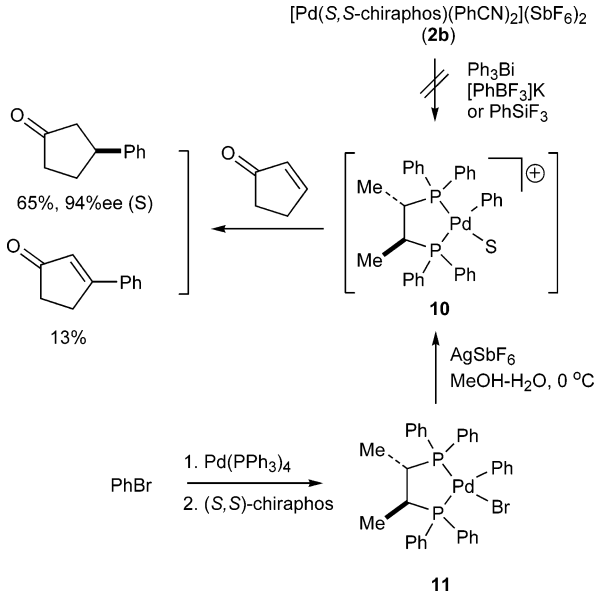
(41) Alcazar-Roman, L. M.; Hartwig, J. F. *Organometallics* **2002**, *21*, 491.

(42) (a) Vineyard, B. D.; Knowles, W. S.; Sabacky, M. J.; Bachman, G. L.; Weinkauff, D. J. *J. Am. Chem. Soc.* **1977**, *99*, 5946. (b) Brown, J. M.; Chaloner, P. A. *J. Am. Chem. Soc.* **1980**, *102*, 3040. (c) Knowles, W. S. *Acc. Chem. Res.* **1983**, *16*, 106. (d) McCulloch, B.; Halpern, J.; Thompson, M. R.; Landis, C. R. *Organometallics* **1990**, *9*, 1392. (e) Giovannetti, J. S.; Kelly, C. M.; Landis, C. R. *J. Am. Chem. Soc.* **1993**, *115*, 4040. (f) Knowles, W. S. *Angew. Chem., Int. Ed.* **2002**, *41*, 1998.

(43) (a) Alcock, N. W.; Brown, J. M.; Derome, A. E.; Lucy, A. R. *J. Chem. Soc., Chem. Commun.* **1985**, 575. (b) Brown, J. M.; Maddox, P. J. *J. Chem. Soc., Chem. Commun.* **1987**, 1276. (c) Spogliarich, R.; Farnetti, E.; Kašpar, J.; Graziani, M.; Cesarotti, E. *J. Mol. Catal.* **1989**, *50*, 19.

(44) For reviews: (a) Brown, J. M. *Chem. Soc. Rev.* **1993**, 235. (b) Gridnev, I. D.; Imamoto, T. *Acc. Chem. Res.* **2004**, *37*, 633.

Scheme 4. Transmetalation Intermediate



ordination of alkene to metal complexes of these traditional ligands. We tried to rationalize the opposite sense of enantioselection displayed by chiraphos and dipamp complexes via structural analysis of the catalytic precursors or intermediates (**2a**,**b**) and by DFT calculations.

Transmetalation between [Pd(*S*,*S*-chiraphos)(PhCN)$_2$](SbF$_6$)$_2$ (**2b**) and Ph_3Bi, [PhBF$_3$]K, or PhSiF$_3$ failed to give the monocationic arylpalladium(II) intermediates **10** (Scheme 4). The previous methods for preparation of cationic phenylpalladium(II) complexes stabilized by PPh_3[26] or RNH_2[41] also failed to provide **10**. Alternatively, **10** prepared in situ by treating [Pd(Ph)(Br)(*S*,*S*-chiraphos)] (**11**) with $AgSbF_6$ reacts with 2-cyclopentenone to give 3-phenylcyclopentanone in 65% yield and with 94% ee within 2 h at 0 °C. The absolute configuration of the product is *S*, in good agreement with that of the catalytic reaction. On the other hand, the corresponding neutral **11** results in no product for periods up to 48 h at 0 °C, thus indicating high reactivity of the cationic complex toward insertion of alkenes.

ORTEP plots of **2b**,**c** are shown in Figure 1. The molecular structure of **2b** displays a slightly twisted square-planar coordination geometry for the palladium(II) atom ligated with two phosphorus atoms of chiraphos and two nitrogen atoms of benzonitrile. The sum of angles around a palladium atom is 360.4°. The bite angle of P−Pd−P (83.6°) is slightly smaller than those of [Pd(dppe)(PhCN)$_2$](BF$_4$)$_2$ (85.0°) and neutral PdCl$_2$(dppe) (85.8°).[45] Two phenyl groups in the upper left and the lower right (A, D) occupy pseudo-axial positions in the chelate ring, whereas the phenyls of another pair (C, B) are in pseudo-equatorial positions. There is a steric hindrance between the equatorial phenyl groups and the two benzonitrile ligands to pressure the left benzonitrile molecule upward and the right one downward with respect to the P−Pd−P plane, thus suggesting that the space is accessible to reactants in the upper left and lower right quadrants. The dihedral angle between the P−Pd−P and N−Pd−N planes is 9.1° with clockwise rotation of the N−Pd−N plane. Such a twisted structure, suggesting free spaces accessible to the reactants, has been reported in a PdCl$_2$(*R*-binap) complex.[46] *cis*-Pt(SnMe$_3$)L$_2$ and *cis*-Pd(SiMe$_3$)$_2$L$_2$ (L = PAr$_3$) have analogous twisted square-planar structures that are fluxional in solution.[47]

On the other hand, the N−Pd−N plane is skewed 10.1° counterclockwise with respect to the P−Pd−P plane to avoid steric strain between benzonitrile and axial phenyl groups, which are constrained to be "edge-on" to the substrates. The axial phenyls, perpendicular to the 2-methoxyphenyl groups, are characteristic of solid-state structures of dipamp complexes. Assuming that the coordination of the substrate would follow the same trend as that of the coordination of benzonitrile, the lower left and the upper right quadrants in **2c** are less hindered. Thus, the benzonitrile molecules in the solid state recognize different quadrants of the precatalysts (**2b**,**c**), corresponding well with the opposite sense of enantioselection observed in the catalyzed reactions of these complexes (Scheme 3). Indeed, a parallel orientation of C=C and Pd−C bonds is achieved when, for example, a planar cyclopentenone ring is placed in the lower right (and lower left) quadrant for *si* coordination, giving an *R* product (**12**). The upper right (and lower left) quadrants are less hindered in **2c**; therefore, *re* coordination of substrates, yielding *S*-products, (**13**) can be analogously expected.

DFT Computational Studies on Substrate Coordination. The solid-state structures of conformationally flexible complexes, in general, cannot be reliably used for discussion of the mechanism of enantioselection, since the solution conformations of real intermediates might differ from the solid-state structures of catalytic precursors.[48] Thus, the mode of substrate coordination to the chiral phosphine−phenylpalladium(II) intermediate (**5**, Ar = Ph) was calculated: i.e., the reaction stage directly preceding the stereodetermining insertion step by DFT computations at the B3LYP/SDD level of theory (Figure 2). Three stable adducts between [Pd(*S*,*S*-chiraphos)(Ph)]$^+$ and 2-cyclopentenone located computationally are shown schematically in **14**−**16**. Although neither *si* nor *re* coordination of the substrate is significantly preferred thermodynamically, only the precursor of the experimentally observed enantiomer giving an *S* product has a conformational minimum with parallel coordination of the C−C double bond to the Pd−P bond (**14**). The reason for stereoselectivity seems to be not the relative stability of the complexes but rather their capability for the next insertion reaction. If the coordination takes place on the opposite *re* face, the next insertion process is retarded, because the parallel orientation of C=C and Pd−P bonds becomes unstable due to the steric hindrance caused by the upper right axial phenyl.

We failed to locate a stable conformation for the adduct between [Pd(S,S-dipamp)(Ph)]$^+$ and 2-cyclohexenone, where the C=C and Pd−C bonds are parallel,

(45) Steffen, W. L.; Palenik, G. J. *Inorg. Chem*. **1976**, *15*, 2432.

(46) Ozawa, F.; Kubo, A.; Matsumoto, Y.; Hayashi, T.; Nishioka, E.; Yanagi, K.; Moriguchi, K. *Organometallics* **1993**, *12*, 4188.

(47) (a) Obora, Y.; Tsuji, Y.; Nishiyama, K.; Ebihara, M.; Kawamura, T. *J. Am. Chem. Soc.* **1996**, *118*, 10922. (b) Tsuji, Y.; Nishiyama, K.; Hori, S.; Ebihara, M.; Kawamura, T. *Organometallics* **1998**, *17*, 507. For a review, see: (c) Tsuji, Y.; Obora, Y. *J. Organomet. Chem*. **2000**, *611*, 343.

(48) Tsuruta, H.; Imamoto, T.; Yamaguchi, K.; Gridnev, I. D. *Tetrahedron Lett*. **2005**, *46*, 2879.

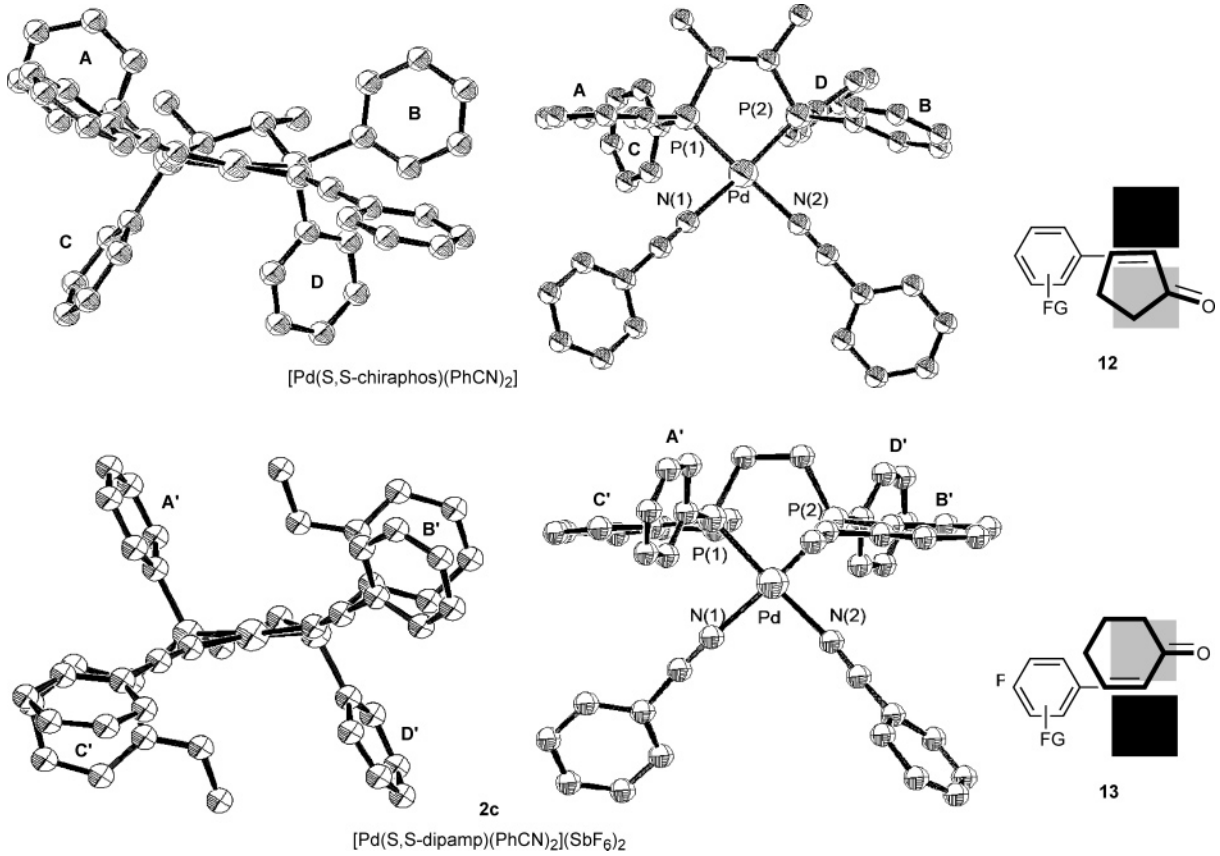


Figure 1. ORTEP diagrams of **2b**,**c** and proposed transition states (**12**, **13**).

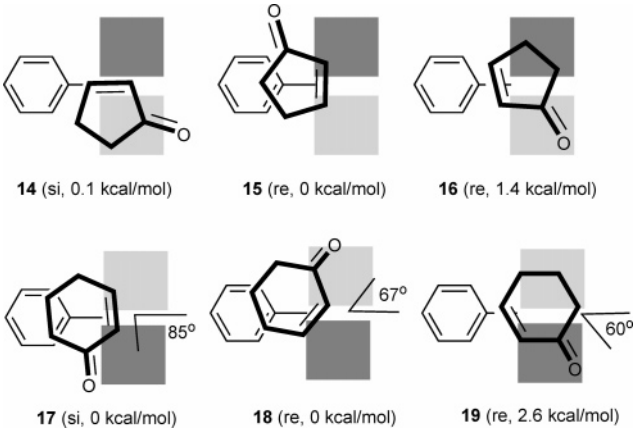


Figure 2. Stable conformations optimized at the B3LYP/SDD level of theory: [Pd(*S*,*S*-chiraphos)(Ph)(2-cyclopentenone)]$^+$ for **14** and **15** and [Pd(*S*,*S*-dipamp)(Ph)(2-cyclopentenone)]$^+$ for **17**−**19**.

but the optimization provided three conformational minimums for *si* coordination (**17**) and *re* coordination of the substrate (**18** and **19**). The cyclohexenone moiety in **18** closer to the proper orientation of the C=C and Pd−C bonds than in **17**, among two conformers which have almost equal energies for *si* (**17**) and *re* coordination (**18**), whereas the *si* coordination of cyclohexenone (**17**) is effectively blocked by steric hindrance between the axial phenyl and the skewed $-(CH_2)_3-$ chain of cyclohexenone. Hence, we conclude that the insertion proceeds from **18** for giving an experimentally observed *R* product.

The mode of substrate coordination in **14** is shown in Figure 3. The phenyl group bonded to a palladium atom

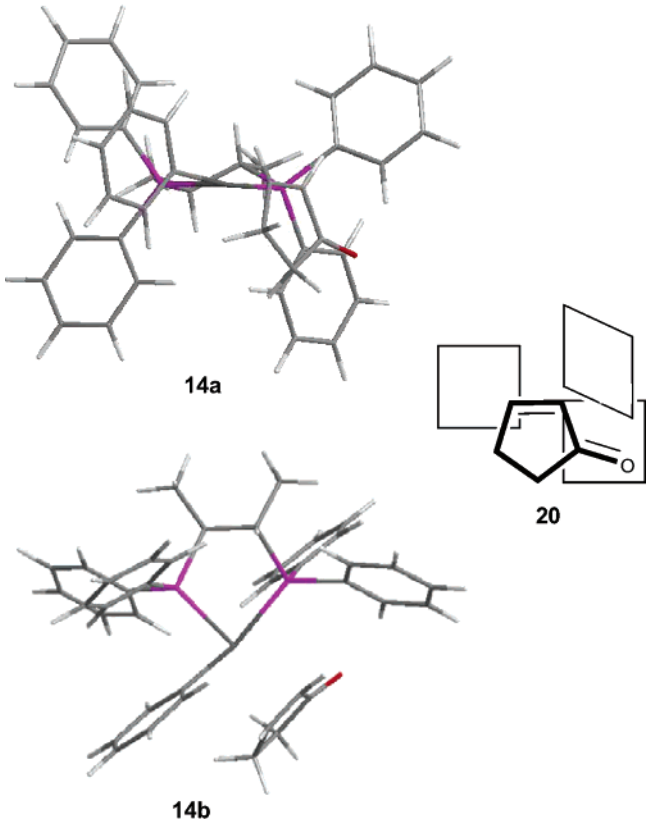


Figure 3. Side and top views of **14**.

is slightly twisted to the upper left area, as was observed for a molecule of benzonitrile in the X-ray structure of **2b** (**14a**). It is interesting that the conformations of two axial P-bound phenyl groups and a Pd-bound phenyl

group are almost coplanar to the cyclopentenone ring (**14b**), whereas the two phenyl groups on palladium and phosphine atoms constitute a free space for coordination of an enone to the metal center (**20**). The efficiency of chiraphos for planar cyclic and acyclic enones and the substitution effects of R^1 and R^3 of enones (**1**), and the participation of P-bound aryl groups in enantioselectivity, can be interpreted by this model.

Experimental Section

Reactions of Ar_3Bi (Table 2, Entry 4). A flask was charged with Ph_3Bi (0.6 mmol) and $Cu(BF_4)_2 \cdot 6H_2O$ (0.76 mmol) and flushed with argon. Methanol (6 mL), 2-cyclohexenone (1 mmol), and water (1 mL) were then added. The mixture was cooled to −5 °C before addition of [Pd(*S,S*-dipamp)$(PhCN)_2$]-$(SbF_6)_2$ (0.04 mmol). After the mixture was stirred for 21 h at −5 °C, chromatography on silica gel gave (*R*)-3-phenylcyclohexanone in 92% yield. The enantiomeric excess (92% ee) was determined by HPLC analysis using Daicel Chiralpak AD (98/2 hexane/2-propanol).

Reactions of $[ArBF_3]K$ (Table 2, Entry 4). To a flask was successively added $[ArBF_3]K$ (1.5 mmol), methanol (6 mL), 2-cyclohexenone (1 mmol), and water (0.6 mL) under argon. [Pd(*S,S*-dipamp)$(PhCN)_2$]$(SbF_6)_2$ (0.03 mmol) was then added at −15 °C. After the mixture was stirred for 21 h, chromatography on silica gel gave (*R*)-3-phenylcyclohexanone in 95% yield. The enantiomer excess (93% ee) was determined by HPLC analysis using Daicel Chiralpak AD (98/2 hexane/2-propanol).

Reactions of $ArSiF_3$ (Table 2, Entry 4). $ArSiF_3$ (2.0 mmol), methanol (6 mL), ZnF_2 (1 mmol), 2-cyclohexenone (1 mmol), and water (0.6 mL) were successively added to a flask under argon. [Pd(*S,S*-dipamp)$(PhCN)_2$]$(SbF_6)_2$ (0.03 mmol) was then added at 0 °C. After the mixture was stirred for 21 h at 0 °C, chromatography on silica gel gave (*R*)-3-phenylcyclohexanone in 83% yield. The enantiomeric excess (92% ee) was determined by HPLC analysis using Daicel Chiralpak AD (98/2 hexane/2-propanol).

Supporting Information Available: Text, tables, and figures giving experimental procedures, compound characterization data, X-ray data, and computational results. This material is available free of charge via the Internet at http://pubs.acs.org.

OM050678T