New Trans-Chelating Ligands and Their Complexes and Catalytic Properties in the Mizoroki−Heck Arylation of Cyclohexene

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New air-stable chelating diphosphine ligands, 1,8-bis(4-(diphenylphosphino)phenyl)anthracene (**2**) and 1,8-bis(4-(diphenylphosphino)-3,5-dimethylphenyl)anthracene (**3**), were synthesized from readily available starting materials. The examination of their coordination modes in Pd(II) and Rh(I) complexes by means of ^{1}H, ^{13}C, and ^{31}P NMR spectroscopy and X-ray analysis revealed that **2** is mainly a trans-coordinating ligand but can also adapt smaller coordination angles, while **3** is "purely" trans-spanning and no formation of identifiable cis-chelated complexes was detected. The catalytic activity of the new compounds was tested in palladium-catalyzed Mizoroki−Heck reactions of aryl bromides with cyclohexene.

Introduction

During the past few decades, enormous efforts have been devoted to the synthesis of transition-metal complexes as promoters for a variety of homogeneously catalyzed transformations. Most of the catalysis-relevant ligands developed in recent years are bidentate ligands that can be literally classified into three groups: (i) cis -chelating ligands, having chelation angles under 100° (represent a vast majority of known ligands),[1] (ii) wide-bite-angle ligands, with chelation angles ranging between 100 and 160°,[2] and (iii) trans-chelating ligands, having chelation angles over 160°.[3] While the reactivities of the transition-metal complexes bearing cis and wide-bite-angle ligands, as well as striking differences in their reactivity, are now well-documented,[4] extensive exploration of trans-chelated transition-metal compounds in catalysis started only in recent years.[5] Several new, very interesting ligands belonging to this family were prepared and studied in the context of their coordination chemistry and potential catalytic applications, demonstrating very unusual and fascinating properties.[6] However, their real synthetic potential is still unexplored.

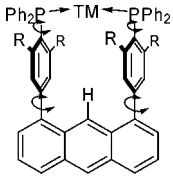

Figure 1. 1,8-Bis(*p*-(diphenylphosphino)phenyl)anthracenes.

As a part of our research program aiming the investigation of such compounds, we became interested in studying the coordination chemistry and catalytic properties of the potentially trans-chelating ligands based on 1,8-bis(*p*-(diphenylphosphino)phenyl)anthracene (Figure 1).

It should be noted that the design and synthesis of effective trans-spanning ligands requires the installation of donor groups at large distance and, therefore, is traditionally associated with certain problems, such as excessive flexibility of the frame (leading to conformational instability),[7] multiple coordination modes (leading to dimerization or oligomerization),[8] etc.[5] The suggested design, however, avoids these structural complications. As we assumed, the planar anthracene-based scaffold enables the preferred trans chelation due to the adequately

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(1) (a) Martell, A. E. *Pure Appl. Chem.* **1968**, *17*, 129. (b) Inoguchi, K.; Sakuraba, S.; Achiwa, K. *Synlett* **1992**, 169. (c) Elsevier, C. J.; Reedijk, J.; Walton, P. H.; Ward, M. D. *Dalton Trans.* **2003**, 1869. (d) Nicolaou, K. C.; Bulger, P. G.; Sarlah, D. *Angew. Chem., Int. Ed.* **2005**, *44*, 4442. (e) Li, Y.-M.; Kwong, F.-Y.; Yu, W.-Y.; Chan, A. S. C. *Coord. Chem. Rev.* **2007**, *251*, 2119. (f) Negishi, E. *Bull. Chem. Soc. Jpn.* **2007**, *80*, 233.

(2) (a) Dierkes, P.; van Leeuwen, P. W. N. M. *J. Chem. Soc., Dalton Trans.* **1999**, 1519. (b) van Leeuwen, P. W. N. M.; Kamer, P. C. J.; Reek, J. N. H. *Pure Appl. Chem.* **1999**, *71*, 1443. (c) Freixa, Z.; van Leeuwen, P. W. N. M. *Dalton Trans.* **2003**, 1890.

(3) Bessel, C. A.; Aggarwal, P.; Marschilok, A. C.; Takeuchi, K. J. *Chem. Rev.* **2001**, *101*, 1031.

(4) (a) Hamann, B. C.; Hartwig, J. F. *J. Am. Chem. Soc.* **1998**, *120*, 3694. (b) van der Veen, L. A.; Keeven, P. H.; Schoemaker, G. C.; Reek, J. N. H.; Kamer, P. C. J.; van Leeuwen, P. W. N. M.; Lutz, M.; Spek, A. L. *Organometallics* **2000**, *19*, 872. (c) van der Veen, L. A.; Keeven, P. K.; Kamer, P. C. J.; van Leeuwen, P. W. N. M. *Dalton Trans.* **2000**, 2105. (d) Guari, Y.; van Strijdonck, G. P.; Boele, M. D.; Reek, J. N.; Kamer, P. C.; van Leeuwen, P. W. N. M. *Chemistry* **2001**, *7*, 475. (e) Kamer, P. C. J.; van Leeuwen, P. W. N. M.; Reek, J. N. H. *Acc. Chem. Res.* **2001**, *34*, 895. (f) Zuidema, E.; Daura-Oller, E.; Carbo, J. J.; Bo, C.; van Leeuwen, P. W. N. M. *Organometallics* **2007**, *26*, 2234.

(5) Freixa, Z.; van Leeuwen, P. W. N. M. *Coord. Chem. Rev.* **2008**, *252*, 1755, and references cited therein.

(6) (a) Reed, F. J. S.; Venanzi, L. M. *Helv. Chim. Acta* **1977**, *60*, 2804. (b) Kuwano, R.; Sawamura, M.; Shirai, J.; Takahashi, M.; Ito, Y. *Bull. Chem. Soc. Jpn.* **2000**, *73*, 485. (c) Freixa, Z.; Beentjes, M. S.; Batema, G. D.; Dieleman, C. B.; van Strijdonck, G. P. F.; Reek, J. N. H.; Kamer, P. C. J.; Fraanje, J.; Goubitz, K.; van Leeuwen, P. W. N. M. *Angew. Chem., Int. Ed.* **2003**, *42*, 1284. (d) Smith, R. C.; Bodner, C. R.; Earl, M. J.; Sears, N. C.; Hill, N. E.; Bishop, L. M.; Sizemore, N.; Hehemann, D. T.; Bohn, J. J.; Protasiewicz, J. D. *J. Organomet. Chem.* **2005**, *690*, 477. (e) Grossman, O.; Azerraf, C.; Gelman, D. *Organometallics* **2006**, *25*, 375. (f) Poorters, L.; Armspach, D.; Matt, D.; Toupet, L.; Choua, S.; Turek, P. *Chem. Eur. J.* **2007**, *13*, 9448. (g) Schnetz, T.; Roeder, M.; Rominger, F.; Hofmann, P. *Dalton Trans.* **2008**, 2238. (h) Mueller, C.; Freixa, Z.; Lutz, M.; Spek, A. L.; Vogt, D.; van Leeuwen, P. W. N. M. *Organometallics* **2008**, *27*, 834.

(7) (a) DeStefano, N. J.; Johnson, D. K.; Lane, R. M.; Venanzi, L. M. *Helv. Chim. Acta* **1976**, *59*, 2674. (b) Kapoor, P. N.; Venanzi, L. M. *Helv. Chim. Acta* **1977**, *60*, 2824. (c) Smith, R. C.; Protasiewicz, J. D. *Organometallics* **2004**, *23*, 4215.

(8) (a) Smith, D. C., Jr.; Gray, G. M. *Chem. Commun.* **1998**, 2771. (b) Smith, D. C., Jr.; Lake, C. H.; Gray, G. M. *Dalton Trans.* **2003**, 2950.

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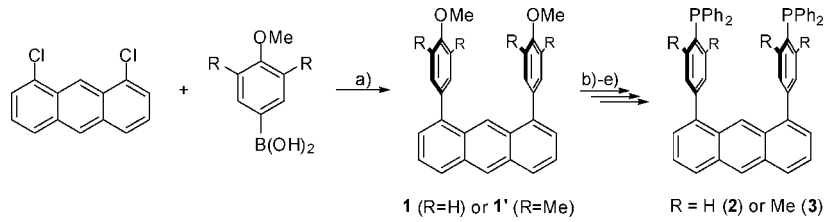
Scheme 1. Preparation of 2 and 3[a]



[a] Reaction conditions: (a) $Pd(OAc)_2$/2-dicyclohexylphosphino-2′,4′,6′-triisopropylbiphenyl, K_3PO_4, toluene (isolated yield: R = H, 81%; R = Me, 73%); (b) BBr_3, DCM (isolated yield: R = H, 95%; R = Me, 90%); (c) Tf_2O, i-Pr_2NEt, DCM, DMAP (isolated yield: R = H, 72%; R = Me, 82%); (d) $Pd(OAc)_2$/dppp, H(O)PPh_2, i-Pr_2NEt, DMSO (isolated yield: R = H, 46%; R = Me, 74%); (e) $HSiCl_3$, TEA, xylene (isolated yield: R = H, 65%; R = Me, 75%).

remote phosphine groups.[9] On the other hand, along with the ligand being *mainly* trans chelating, some flexibility in coordination will be allowed due to a limited rotation of the phosphine donors and phenyl rings around C−P and C−C bonds (Figure 1). This ability of a ligand to adapt different coordination angles within a certain range is an important factor in catalysis, because it assists in the stabilization of different intermediates that may form over the course of a catalytic cycle. In this particular case, this range may be controlled by installing bulky substituents at the 3,5- and 3′,5′-positions of the phenyl rings. At the same time, the all-aromatic scaffold ensures the conformational stability of the resulting complexes.

Finally, the ligand scaffold is modular and can be easily prepared using reliable cross-coupling methodology.

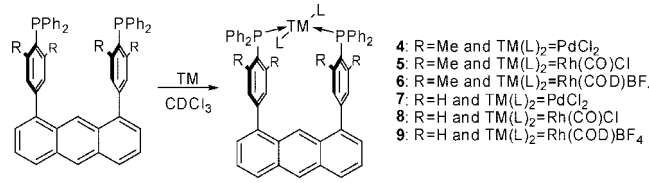
Herein we wish to report on the synthesis, characterization, and catalytic properties of transition-metal complexes bearing the new trans-spanning anthracene-based ligands 1,8-bis-(4-(diphenylphosphino)phenyl)anthracene (**2**) and 1,8-bis(4-(diphenylphosphino)-3,5-dimethylphenyl)anthracene (**3**). As we found, in addition to interesting structures, the new ligand **2** demonstrates high reactivity and unusually high regioselectivity in palladium-catalyzed Mizoroki−Heck reactions of aryl bromides with cyclohexene.

Results and Discussion

Ligands and Complexes. Scheme 1 summarizes the synthetic pathway to **2** and **3** from 1,8-dichloroanthracene, which can be prepared from the commercially available 1,8-dichloroanthraquinone. As was mentioned, the whole synthesis relies on cross-coupling chemistry and starts from the double Suzuki reaction leading to **1** (R = H) or **1′** (R = Me) in good to excellent yield.[10] The products were converted into the corresponding triflates after deprotection of the *p*-methoxy groups and coupled with diphenylphosphine oxide using well-established palladium-catalyzed protocols. Phosphine oxide reduction at the final step yields the desired compounds in 17−25% overall yield (five steps). Notably, **2** and **3** are perfectly soluble in all common organic solvents and air-stable, so that they can be kept for months on a shelf without notable oxidation.

$^{31}P\{^1H\}$ NMR spectra of **2** and **3** in $CDCl_3$ display single resonance frequencies at δ −6.1 and −15.6 ppm, respectively, which are ascribed to the identical phosphine groups. Recording spectra at lower temperatures (−30 °C) indicated no presence of possible rotameric species (face to face or face to tail).

Scheme 2. Preparation of Transition-Metal Complexes



In order to study the coordination preferences of the new ligands, they were allowed to react with different transition-metal precursors, as shown in Scheme 2. The products were studied in solution using NMR, and representative examples were isolated and characterized by X-ray analysis.

Initially, ligand **3** was reacted with $PdCl_2(CH_3CN)_2$ and $Rh_2(CO)_2Cl_2$ in deuterated chloroform at room temperature.

NMR measurements indicated that the formation of the complexes **4** and **5** was complete within 2−3 h. The $^{31}P\{^1H\}$ NMR spectra of **4** and **5** displayed a sharp singlet with a resonance frequency of 19.4 ppm for **4** and a doublet centered at 31.9 ppm with the coupling constant J_{Rh-P} = 96 Hz for **5**. Complexes **4** and **5** form cleanly, and only minor impurities were detected by NMR.

Suitable single crystals of **4** and **5**, grown by the slow diffusion of pentane into their saturated solutions in chloroform at room temperature, were subjected to X-ray diffraction analysis.

As expected, complexes **4** and **5** exist in almost perfect trans-spanned form (the ORTEP illustrations are given in Figure 2).

We found that the palladium center in **4** is only slightly distorted from the square-planar geometry. For example, the observed P(1)−Pd−P(2) and Cl(1)−Pd−Cl(2) angles and P(1)−P(2) intramolecular distance between the two phosphorus groups for **4** are 168.53°, 179.18(2)° and 4.67 Å, respectively. The corresponding parameters for **5** are 167.68°, 179.02°,and 4.657 Å. The P−metal, Cl−metal and CO−metal bond lengths lie within the normal range of *trans*-diphosphine complexes.[5,11]

Surprisingly, we found that the bridging 3,5-dimethylphenyl rings are not coplanar, despite the bulkiness of the methyl substituents. Thus, the ring planes converge with a sharp angle of 42.30° in **4** and a similar angle in **5**.

Reactions of the ligand **2** with the same transition-metal precursors also led to complete complexation. For example, the $^{31}P\{^1H\}$ NMR spectra of complexes **7** and **8**, taken from the reaction mixtures, indicated the formation of a predominant

(9) The binding properties of 1,8-bis(*p*-(diphenylphosphino)phenyl)anthracenes may tentatively be compared to those of 1,8-bis(diphenylphosphino)anthracene. The latter, however, is prone to carbometalation reactions. See for example: Haenel, M. W.; Jakubik, D.; Krueger, C.; Betz, P. *Chem. Ber.* **1991**, *124*, 333.

(10) (a) Old, D. W.; Wolfe, J. P.; Buchwald, S. L. *J. Am. Chem. Soc.* **1998**, *120*, 9722. (b) Barder, T. E.; Walker, S. D.; Martinelli, J. R. *J. Am. Chem. Soc.* **2005**, *127*, 4685.

(11) (a) Ovchinnikov, M. V.; Brown, A. M.; Liu, X.; Mirkin, C. A.; Zakharov, L. N.; Rheingold, A. L. *Inorg. Chem.* **2004**, *43*, 8233. (b) Burger, S.; Therrien, B.; Suess-Fink, G. *Helv. Chim. Acta* **2005**, *88*, 478. (c) Morgan, B. P.; Smith, R. C. *J. Organomet. Chem.* **2008**, *693*, 11.

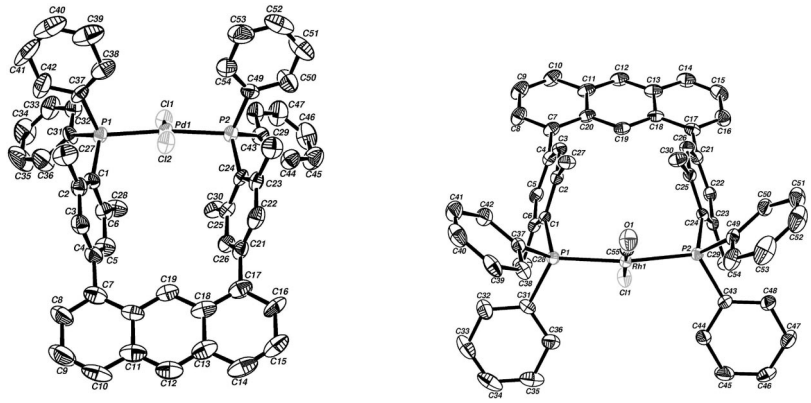


Figure 2. ORTEP drawings (50% probability ellipsoids) of the structures of **4** and **5**. Hydrogen atoms and solvent molecules are omitted for clarity. Selected bond lengths (Å) and angles (deg) for **4**: Pd1−Cl1 = 2.3010(17), Pd1−Cl2 = 2.3029(17), Pd1−P1 = 2.3636(18), Pd1−P2 = 2.3679(18), P1−P2 = 4.708; Cl1−Pd1−Cl2 = 179.18(7), P1−Pd1−P2 = 168.53(6). Selected bond lengths (Å) and angles (deg) for **5**: Rh1−Cl1 = 2.3719(7), Rh1−C55 = 1.819(3), C55−O1 = 1.114(3), Rh1−P1 = 2.3391(6), Rh1−P2 = 2.3450(7), P1−P2 = 4.657; Cl1−Rh1−C55 = 179.03(8), P1−Rh1−P2 = 167.68(2).

species accompanied by only insignificant impurities. Complex **7** exhibited a single resonance frequency at 23.1 ppm that is assigned to the identical phosphine donors. Complex **8** appeared as a doublet at 32.5 ppm with a coupling constant of J_{Rh-P} = 93.

Compounds **7** and **8** displayed chemical shifts and coupling patterns very similar to those of the fully characterized **4** and **5**; therefore, there is no reason to suspect that they have a different (cis) coordination behavior.

In order to confirm experimentally the assumed ability of the anthracene-based scaffolds to adapt smaller coordination angles, we attempted the synthesis of cationic Rh(I) complexes from the new ligands and strongly cis-directing $[Rh(COD)_2]BF_4$. Unlike previous experiments, we observed a different coordination behavior of **2** and **3** toward this precursor.

According to ^{31}P NMR analysis, the reaction of **2** with $[Rh(COD)_2]BF_4$ in deuterated chloroform led almost immediately to the formation of one major, apparently cis-chelated product, **9** (Scheme 1); a doublet centered at 25.9 ppm with a coupling constant of 108 Hz may be indicative of cationic *cis*-diphosphine rhodium complexes.[12] To confirm the structural arrangement at the metal center of **9**, a single crystal grown from a chloroform/hexane mixture was subjected to an X-ray analysis.

Indeed, we found that **9** is cis chelated with P(1)−Rh(1)−P(2) = 95.0°; an ORTEP illustration is given in Figure 3. It is remarkable that the rigid all-aromatic scaffold of **3** experiences a significant bond deformation in order to achieve such a small coordination angle. For example, the deviation of the P(1)−C(1) and C(4)−C(7) bonds from the bridging ring plane averages 0.296 Å. Other bond lengths and angles are within the normal range.[13]

The reaction of **3** with the cationic $[Rh(COD)_2]BF_4$, in contrast, resulted in the formation of multiple unidentifiable compounds according to $^{31}P\{^1H\}$ NMR analysis at various temperatures (−30 °C to +30 °C). Apparently, the steric bulk of the substituents at the 3,5-positions of the ligand limits the rotation of the phosphine donors and conflicts with the strong cis-directing effect of the COD spectator.

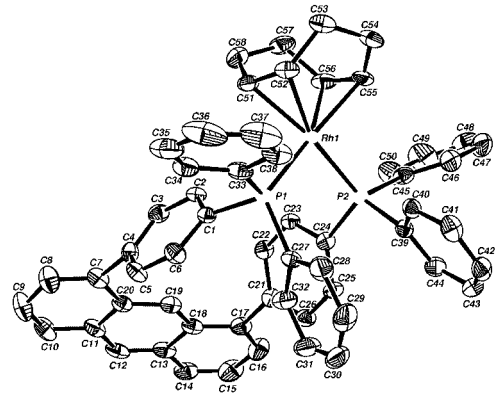


Figure 3. ORTEP drawing (50% probability ellipsoids) of the structure of **9**. Hydrogen atoms, counterion, and solvent molecules are omitted for clarity. Selected bond lengths (Å) and angles (deg) for **9**: Rh1−C52 (= 2.245(5), Rh1−C51 = 2.221(5), Rh1−C55 = 2.226(5), Rh1−C56 = 2.230(5), Rh1−P1 = 2.3576(13), Rh1−P2 = 2.3530(13), P1−P2 = 3.473; P1−Rh1−P2 = 95.00(5), C55−Rh1−C56=78.8(2),C51−Rh1−P1=89.62(15),C55−Rh1−P2 = 92.32(14).

Molecular modeling performed using Gaussian 03 at the semiempirical PM3 level[14] starting from the X-ray coordinates and applying constraints revealed that coordination angles of ca. 120° can be conformed by **3** (total energy lies within the 3 kcal/mol flexibility range). However, further constraining of the ligand geometry to the ideal cis arrangement displays a very high barrier of 9.1 kcal/mol which, obviously, can not be easily accessed (Figure 4).

Catalytic Studies. To check the catalytic activity of the new ligands, we chose palladium-catalyzed Mizoroki−Heck olefination as a model reaction.

The reaction has become, arguably, one of the most powerful methods in synthetic organic chemistry for the construction of carbon−carbon bonds.[15] Over the years, many major problems of Heck-type chemistry have been solved: new catalysts and protocols are now available to activate less reactive substrates and to perform transformations in a chemo- and stereoselective fashion. In contrast, the problem of regioselectivity has only

(12) (a) Dubrovina, N. V.; Tararov, V. I.; Monsees, A.; Spannenberg, A.; Kostas, I. D.; Boerner, A. *Tetrahedron: Asymmetry* **2005**, *16*, 3640. (b) Tsuchikama, K.; Kuwata, Y.; Tahara, Y.-K.; Yoshinami, Y.; Shibata, T. *Org. Lett.* **2007**, *9*, 3097.

(13) (a) Stoop, R. M.; Mezzetti, A.; Spindler, F. *Organometallics* **1998**, *17*, 668. (b) Liu, C.; Widenhoefer, R. A. *Organometallics* **2002**, *21*, 5666.

(14) (a) Frisch, M. J. Gaussian 03, Revision D.01; Gaussian, Inc., Wallingford, CT, 2004. (b) Stewart, J. J. P. *J. Comput. Chem.* **1991**, *12*, 320. (c) Stewart, J. J. P. *J. Mol. Mod.* **2004**, *10*, 155.

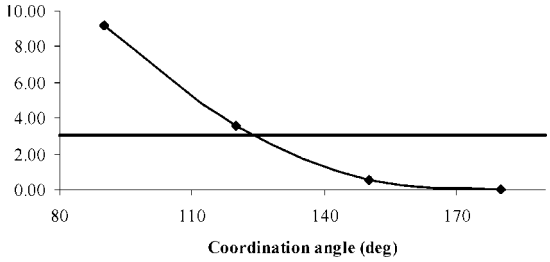


Figure 4. Potential energy diagram for **9**.

been solved partially. For example, predominant formation of one double-bond regioisomer is still only possible in intramolecular transformations or intermolecular reactions with electron-rich/-deficient olefins.[16] Intermolecular arylation of simple electron-neutral alkenes, however, normally yields complex mixtures of all possible regioisomeric products.[15a,17]

In principle, the distribution of regioisomeric products in this transformation originates from the reversibility of the product-forming step (Scheme 3). The kinetic product B is accumulated if reductive elimination of HX is fast, while the accumulation of thermodynamic products A and C (depending on the ring size) occurs if reductive elimination is slow. The majority of known catalytic systems lead, however, to the formation of impractical mixtures.[15a]

There is a very limited number of protocols discussing regioselectivity issues in such reactions. For example, Beller suggested a base dependence of the regioselectivity in such cases and demonstrated that good regioselectivity (toward the thermodynamic product) may be achieved when sodium acetate in DMSO/DMA was employed as a base.[17b] In this context, it would be interesting to test whether the same effect may be achieved under ligand-assisted conditions.

The idea behind this hypothesis is as follows: unlike wide-bite-angle ligands which are known to enhance the rate of reductive elimination reactions,[4b,e] purely trans-spanning ligands should simply shut it down.[18] However, taking into account that rigid trans-spanning ligands unable to adapt smaller coordination angles are very rare (if they exist at all),[19] one could expect just a deceleration of the reductive elimination reaction with complexes bearing such ligands. If so, predominant formation of the thermodynamic product may be expected.

Our initial experiments have clearly demonstrated that the catalyst derived from $Pd(OAc)_2$/**2** is indeed an efficient and *regioselective* promoter for the Heck reaction between aryl bromides and cyclohexene.

A short optimization study revealed that the reaction between bromobenzene (1 equiv) and cyclohexene (1.3 equiv) goes to completion in the presence of 1 mol % of $Pd(OAc)_2$/**2** in DMF and sodium carbonate as a base at 90 °C.

Under these conditions, a series of differently substituted aryl bromides were allowed to react with cyclohexene as well as some other olefins. The yields and selectivities are given in Table 1.

The results of these experiments are very encouraging (entries 2−6, Table 1): (i) full conversion was achieved with electron-deficient, electron neutral and electron-rich aryl bromides; (ii) yields vary from good to excellent (the missing percentage indicates the formation of homocoupled species); (iii) the regioselectivity toward 4-phenylcyclohex-1-ene (the thermodynamic product in this case)[17b] is practical (81% or higher, depending on the electronic parameters of the substrates).

When **2** was replaced with TPP and Xantphos under the same reaction conditions, both the yields and selectivity became unsatisfactory (entries 9 and 10, Table 1). These blank experiments clearly show that the reaction outcome in this case is ligand-controlled.

Thus, from our point of view, the results support the hypothesis that trans-chelating ligands can induce isomerization of a Heck product toward a thermodynamic product due to a slow reductive elimination step. Also remarkably, the rigid **3** was found inactive in the Heck reaction, apparently due to insufficient flexibility and its inability to form cis-chelated species.

Another interesting point that should be noted is the relatively mild reaction conditions required to drive the reaction to completion. Usually, only "privileged" olefins (styrene or alkyl acrylates) may be arylated under temperatures under 80 °C. Using $Pd(OAc)_2$/**2** as a catalyst, "difficult" substrates (cycloalkenes) react at 90 °C, while the reaction temperature for the "privileged" alkenes does not exceed 50 °C (entries 7 and 8, Table 1). We suspect that the higher reactivity of our catalyst might be attributed to the tendency of trans-chelated complexes to form more electrophilic cationic species due to a strong trans effect exerted by the aryl ligand.[20] Such cationic species are known by their affinity toward olefinic ligands and should facilitate the reaction (Scheme 4).[21]

To conclude, we prepared two new representatives of the trans-chelating ligands and studied their coordination to different palladium and rhodium precursors. We found that in both the sterically constrained 1,8-bis(4-(diphenylphosphino)-3,5-dimethylphenyl)anthracene (**3**) and less sterically demanding 1,8-bis(4-(diphenylphosphino)phenyl)anthracene (**2**) the trans chelation is preferred. However, only **2** has a sufficient flexibility range to adapt smaller chelation angles. As a consequence, only **2** was found active in reactions where the formation of cis-chelated species over the course of the catalytic cycle is obligatory.

Our preliminary catalytic studies disclosed very interesting reactivity of the trans-spanning ligands and, therefore, will be extended to include kinetic studies.

(15) (a) Beletskaya, I. P.; Cheprakov, A. V. *Chem. Rev.* **2000**, *100*, 3009. (b) Beller, M.; Riermeier, T. H.; Stark, G. In *Transition Metals for Organic Synthesis*; Beller, M., Bolm, C., Eds.; VCH: Weinheim, Germany, 1998; p 208. (c) Tsuji, J. *Palladium Reagents and Catalysts*; Wiley: Chichester, U.K., 1995. (d) Heck, R. F. In *Comprehensive Organic Synthesis*; Trost, B. M., Flemming, I., Eds.; Pergamon Press: Oxford, U.K., 1991; Vol. 4, p 833.

(16) (a) Stadler, A.; von Schenck, H.; Vallin, K. S. A.; Larhed, M.; Hallberg, A. *Adv. Synth. Catal.* **2004**, *346*, 1773. (b) Mo, J.; Xiao, J. *Angew. Chem., Int. Ed.* **2006**, *45*, 4152. (c) Amatore, C.; Godin, B.; Jutand, A.; Lemaitre, F. *Organometallics* **2007**, *26*, 1757.

(17) (a) de Meijere, A.; Meyer, F. *Angew. Chem.* **1994**, *106*, 2473. (b) Hartung, C. G.; Kohler, K.; Beller, M. *Org. Lett.* **1999**, *1*, 709.

(18) (a) Gillie, A.; Stille, J. K. *J. Am. Chem. Soc.* **1980**, *102*, 4933. (b) Sawamura, M.; Sudoh, M.; Ito, Y. *J. Am. Chem. Soc.* **1996**, *118*, 3309.

(19) (a) Jimenez-Rodriguez, C.; Roca, F. X.; Bo, C.; Benet-Buchholz, J.; Escudero-Adan, E. C.; Freixa, Z.; van Leeuwen, P. W. N. M. *Dalton Trans.* **2005**, 268. (b) Azerraf, C.; Grossman, O.; Gelman, D. *J. Organomet. Chem.* **2007**, *692*, 761.

(20) The formation of highly active colloidal species upon dissociation of the ligand may also be suspected (see for example, Phan, N. T. S.; Van Der Sluys, M.; Jones, C. W *Adv. Synth. Catal.* **2006**, *348*, 609). However, we believe that this is not our case. We did not observe the precipitation of palladium metal over the course of the reaction—usually, the reaction mixture remains brown. In addition, the high selectivity of our catalyst strongly implies ligand assistance.

(21) (a) House, H. O.; Ghali, N. I.; Haack, J. L.; VanDerveer, D. *J. Org. Chem.* **1980**, *45*, 1807. (b) Jutand, A. *Eur. J. Inorg. Chem.* **2003**, 2017. (c) Svennebring, A.; Sjoeberg, P. J. R.; Larhed, M.; Nilsson, P. *Tetrahedron* **2008**, *64*, 1808.

Scheme 3. Plausible Mechanism for the Mizoroki−Heck Reaction

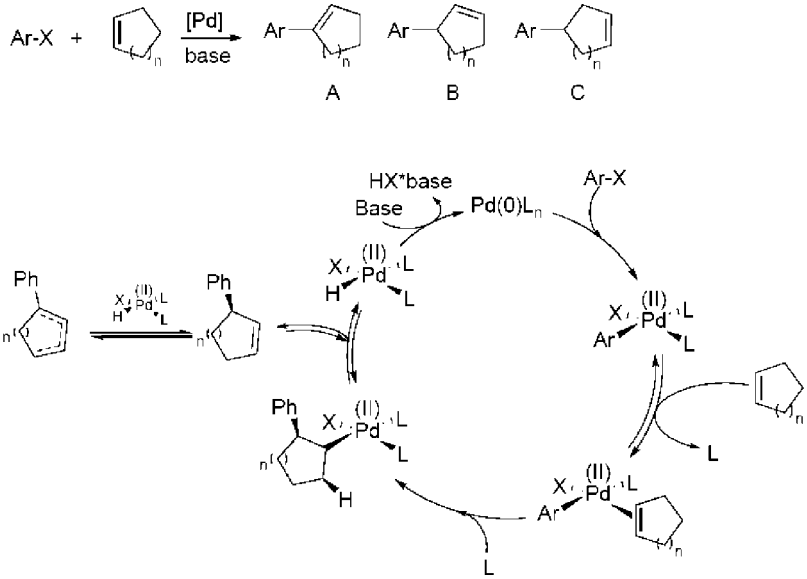
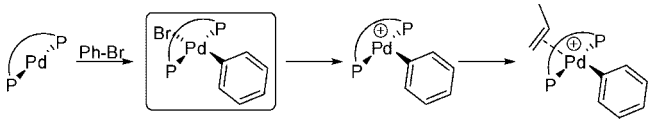


Table 1. Representative Results of Heck Arylation of Alkenes[a]

entry no.	yield (%)[c]	conversn (%)[b]	cat.	olefin	R	selectivity (A:B:C)[d]
1	H	cyclohexene	Pd(OAc)$_2$/**3**			
2	H	cyclohexene	Pd(OAc)$_2$/**2**	>99	82	10:5:85
3	4-CH_3	cyclohexene	Pd(OAc)$_2$/**2**	>99	88	16:3:81
4	4-$COCH_3$	cyclohexene	Pd(OAc)$_2$/**2**	>99	95	5:2:93
5	4-OCH_3	cyclohexene	Pd(OAc)$_2$/**2**	>99	71	7:18:78
6	4-$COCH_3$	1-phenyl-1-cyclohexene	Pd(OAc)$_2$/**2**	no reacn		
7[e]	4-$COCH_3$	styrene	Pd(OAc)$_2$/**2**	<99	80	99% (*E*)-4-acetylstilbene
8[e]	4-$COCH_3$	*tert*-butyl acrylate	Pd(OAc)$_2$/**2**	<99	91	99% (*E*)-*tert*-butyl 3-(4-acetylphenyl)acrylate
9	4-$COCH_3$	cyclohexene	Pd(OAc)$_2$/**PPh_3**	32	N/A	16:31:53
10	4-$COCH_3$	cyclohexene	Pd(OAc)$_2$/**Xantphos**	54	N/A	11:52:37

[a] Conditions: aryl bromide (1 mmol), cyclohexene (1.3 mmol), Pd(OAc)$_2$ (0.02 mmol), **2** (0.03 mmol), K_2CO_3 (2 mmol), DMF (3 mL), 90 °C for 12 h. [b] Determined by GC (dodecane as an internal standard). [c] Isolated yield of mixtures of all regioisomers (average of two runs). [d] Determined by GC. [e] The reactions were conducted at 50 °C for 12 h.

Scheme 4. Formation of Cationic Pd(II) Species



Experimental Section

All manipulations were performed using standard Schlenk techniques under an atmosphere of dry N_2. All chemicals were purchased elsewhere and used without further purification. 1,8-Dichloroanthracene was prepared from commercially available starting materials following the published procedure.[6e] NMR spectra were recorded on a Bruker instrument operating at 400 MHz for protons, 100 MHz for carbons, and 121 MHz for phosphorus. Diffraction data were collected with a Bruker APEX CCD instrument (Mo Kα radiation (λ = 0.710 73 Å). Crystals were mounted onto glass fibers using epoxy. Single-crystal reflection data were collected on a Bruker APEX CCD X-ray diffraction system controlled by a Pentium-based PC running the SMART software package.[22] The integration of data frames and refinement of cell structure were done by the SAINT+ program package.[23] Refinement of the structure on F^2 was carried out by the SHELXTL software package.[24] Further information may be found in the Supporting Information.

1,8-Bis(4-methoxyphenyl)anthracene. A mixture of 1,8-dibromoanthracene (3 g, 8.9 mmol), (4-methoxyphenyl)boronic acid (3.4 g, 22 mmol), K_3PO_4 (7.6 g, 36 mmol), Pd(OAc)$_2$ (20 mg, 0.089 mmol), and 2-(dicyclohexylphosphino)-2′,4′,6′-triisopropylbiphenyl (64 mg, 0.133 mmol) in dry toluene (30 mL) under a nitrogen atmosphere was heated with stirring at 80 °C for 12 h. After the mixture was cooled to room temperature, the solvent was removed in vacuo and the residue was crystallized from toluene to give the product (2.8 g, 81% yield). ^{1}H NMR ($CDCl_3$): δ 8.67 (s, 1H), 8.54 (s, 1H), 8.03 (d, J = 8.8 Hz, 2H), 7.54 (dd, J = 6.8 Hz, J = 1.6 Hz, 2H), 7.51 (d, J = 18.8 Hz, 4H), 7.41 (d, J = 6 Hz, 2H), 7.00 (d, J = 8.8 Hz, 4H), 3.89 (s, 6H). ^{13}C NMR: δ 158.96, 140.2, 132.9, 131.9, 131.0, 130.2, 127.2, 126.6, 125.85, 125.30, 124.14, 113.67, 55.34. Anal. Calcd for $C_{28}H_{22}O_2$: C, 86.13; H, 5.68. Found: C, 86.20; H, 5.61.

1,8-Bis(4-hydroxyphenyl)anthracene. To a solution of 1,8-bis(4-methoxyphenyl)anthracene (2.8 g, 7.2 mmol) in dry CH_2Cl_2 (120 mL) was slowly added a solution of BBr_3 (2.1 mL, 21.5 mmol) at −78 °C under nitrogen. The reaction mixture was stirred at room temperature for 3 h and quenched carefully with 10% HCl at 0 °C. It was then extracted with ethyl acetate, and the organic layer was dried over anhydrous $MgSO_4$. After evaporation under reduced pressure the residue was precipitated with methanol to give the

(22) SMART-NT, V. 5.6; Bruker AXS GMBH, Karlsruhe, Germany, 2002.

(23) SAINT-NT, V. 5.0; Bruker AXS GMBH, Karlsruhe, Germany, 2002.

(24) SHELXTL-NT, V. 6.1; Bruker AXS GMBH, Karlsruhe, Germany, 2002.

pure product (2.5 g, 95% yield). ^{1}H NMR (DMSO): δ 8.73 (s, 1H), 8.68 (s, 1H), 8.08 (d, J = 8.4 Hz, 2H), 7.57 (dd, J = 8.4 Hz, J = 1.6 Hz, 2 H), 7.41 (d, J = 2 Hz, 4H), 7.37 (d, J = 2 Hz, 2 H), 6.90 (d, J = 8.4 Hz, 2 H). ^{13}C NMR: δ 157.3, 140.2, 132.0, 131.4, 130.9, 129.8, 127.4, 127.2, 126.4, 126.0, 115.7. Anal. Calcd for $C_{26}H_{18}O_2$: C, 86.16; H, 5.01. Found: C, 85.93; H, 5.14.

1,8-Bis(4-(((trifluoromethyl)sulfonyl)oxy)phenyl)anthracene. To a mixture of 1,8-bis(4-hydroxyphenyl)anthracene (2.4 g, 6.6 mmol), diisopropylethylamine (2.8 mL), and a few crystals of DMAP in dry CH_2Cl_2 (100 mL) was slowly added 2.2 mL of $(Tf)_2O$ (13.2 mmol) at 0 °C under nitrogen. The reaction mixture was stirred at room temperature for 15 min, extracted with CH_2Cl_2, and washed with water three times. The organic layer was dried over $MgSO_4$. After evaporation under reduced pressure, silica gel column chromatography (hexane/ethyl acetate 90/10) gave the product (3.0 g, 72% yield). ^{1}H NMR ($CDCl_3$): δ 8.60 (s, 1H), 8.32 (s, 1H), 8.11 (d, J = 8.8 Hz, 2H), 7.57 (t, J = 6.8 Hz, 2H), 7.55 (d, J = 15.6 Hz, 4H), 7.43 (d, J = 6.8 Hz, 2H), 7.33 (d, J = 8.4 Hz, 4H). ^{13}C NMR: δ 148.8, 140.7, 132.0, 138.3, 131.5, 129.9, 128.4, 127.3, 126.6, 125.3, 122.6, 121.2.

1,8-Bis((4-diphenylphosphinyl)phenyl)anthracene. To a mixture of 1,8-bis(4-(((trifluoromethyl)sulfonyl)oxy)phenyl)anthracene (2.3 g, 3.7 mmol), diphenylphosphine oxide (3.9 g, 2.2 mmol), $Pd(OAc)_2$ (83 mg, 0.37 mmol), and 1,3-bis(diphenylphosphino-)propane (150 mg, 0.37 mmol) were added dry DMSO (30 mL) and diisopropylethylamine (4.9 mL, 38.4 mmol), and the mixture was heated with stirring at 100 °C for 12 h. After the mixture was cooled to room temperature, the solvent was removed by distillation and the residue was precipitated with methanol to give the pure product (1.6 g, 59% yield). ^{1}H NMR ($CDCl_3$): δ 8.80 (δs, 1H), 8.61 (s, 1H), 8.10 (d, J = 8.8 Hz, 2H), 7.76 (m, 16H), 7.60 (m. 14H), 7.40 (d, J = 5.6 Hz, 2H), 7.76 (m, 16H), 7.68 (m, 14H), 7.60 (d, J = 1.6 Hz, 2H). ^{31}P NMR: δ 28.45 (s). ^{13}C NMR: δ 144.4, 139.1, 133.0, 132.4, 132.1, 131.8, 131.4, 130.0, 129.6, 128.7, 128.5, 127.8, 127.7, 125.3, 122.4.

1,8-Bis((4-diphenylphosphino)phenyl)anthracene (2). To a mixure of 1,8-bis((4-diphenylphosphinyl)phenyl)anthracene (1.6 g, 2.2 mmol) and diisopropylethylamine (3 mL, 15.5 mmol) in xylene (30 mL) was added dropwise trichlorosilane (3 mL, 22 mmol) at 0 °C. After the addition was complete, the mixture was heated with stirring at 120 °C for 12 h. After the reaction mixture was cooled to room temperature, 30% aqueous NaOH (7 mL) was added. The organic layer was separated and dried over $MgSO_4$, and the solvent was removed in vacuo. The residue was precipitated with methanol to give the pure product (1.0 g, 65% yield). ^{1}H NMR ($CDCl_3$): δ 8.80 (s, 1H), 8.57 (s, 1H), 8.06 (d, J = 8.4 Hz, 2H), 7.56 (m, 6H), 7.44 (m, 26H). ^{31}P NMR: δ −6.1 (s). ^{13}C NMR: δ 140.7, 139.9, 137.3, 136.5, 134.0, 133.3, 133.2, 131.9, 130.0, 128.7, 128.6, 127.9, 127.1, 125.3, 123.4. Anal. Calcd for $C_{50}H_{36}P_2$: C, 85.94; H, 5.19. Found: C, 85.93; H, 5.29.

1,8-Bis(4-methoxy-3,5-dimethylphenyl)anthracene. The procedure was as described for 1,8-bis(4-methoxyphenyl)anthracene (73% yield). ^{1}H NMR ($CDCl_3$): δ 8.67 (s, 1H), 8.53 (s, 1H), 8.03 (d, J = 8.8 Hz, 2H), 7.53 (dd, J = 6.8 Hz, J = 1.6 Hz, 2H), 7.38 (d, J = 6.4 Hz, 2H), 7.12 (s, 4H), 3.80 (s, 6H) 2.31 (s, 12H). ^{13}C NMR: δ 156.2, 140.4, 136.1, 131.8, 130.3, 130.3, 130.3, 127.3, 126.7, 125.8, 125.1, 124.1, 59.7, 16.1. Anal. Calcd for $C_{32}H_{30}O_2$: C, 86.06; H, 6.77. Found: C, 85.89; H, 6.68.

1,8-Bis(4-hydroxy-3,5-dimethylphenyl)anthracene. The procedure was as described for 1,8-bis(4-hydroxyphenyl)anthracene (90% yield). ^{1}H NMR ($CDCl_3$): δ 8.72 (s, 1H), 8.51 (s, 1H), 8.01 (d, J = 8.8 Hz, 2H), 7.52 (dd, J = 6.8 Hz, J = 2 Hz, 2H), 7.37 (d, J = 8 Hz, 2H), 7.09 (s, 4H), 2.27 (s, 12H). ^{13}C NMR: δ 151.4, 140.5, 132.6, 131.8, 130.4, 130.1, 127.1, 126.5, 125.7, 125.2, 124.2, 122.5, 15.9. Anal. Calcd for $C_{30}H_{26}O_2$: C, 86.09; H, 6.26. Found: C, 86.31; H, 6.39.

1,8-Bis(4-(((trifluoromethyl)sulfonyl)oxy)-3,5-dimethylphenyl)anthracene. The procedure was as described for 1,8-bis(4-(((trifluoromethyl)sulfonyl)oxy)phenyl)anthracene (82% yield). ^{1}H NMR ($CDCl_3$): δ 8.56 (δs, 1H), 8.33 (s, 1H), 8.08 (d, J = 8.8 Hz, 2H), 7.56 (dd, J = 6.8 Hz, J = 1.6 Hz, 2H), 7.38 (d, J = 7.6 Hz, 2H), 7.17 (s, 4H), 2.38 (s, 12H). ^{13}C NMR: δ 145.9, 140.3, 138.8, 131.6, 131.2, 130.1, 128.1, 127.0, 126.2, 125.2, 17.1.

1,8-Bis(4-(diphenylphosphinyl)-3,5-dimethylphenyl)anthracene. The procedure was as described for 1,8-bis(4-(diphenylphosphinyl)phenyl)anthracene (74% yield). ^{1}H NMR ($CDCl_3$): δ 8.90 (δs, 1H), 8.60 (s, 1H), 8.08 (d, J = 8 Hz, 2H), 7.74 (m, 9H), 7.57 (m, 15H), 7.40 (d, J = 7.2 Hz, 2H), 2.19 (s, 12H). ^{31}P NMR: δ 30.09 (s). ^{13}C NMR: δ 144.0, 144.0, 139.1, 136.0, 135.0, 131.8, 131.6, 129.7, 128.9 128.6, 128.4, 127.7, 127.6, 125.2, 122.6, 24.4.

1,8-Bis(4-(diphenylphosphino)-3,5-dimethylphenyl)anthracene (3). The procedure was as described for 1,8-bis(4-(diphenylphosphino)phenyl)anthracene (75% yield). ^{1}H NMR ($CDCl_3$): δ 9.03 (s, 1H), 8.59 (s, 1H), 8.07 (d, J = 8.4 Hz, 2H), 7.57 (t, J = 7.2 Hz, 2H), 7.45 (d, J = 6.4 Hz, 2H), 7.37 (m, 24H). ^{31}P NMR: δ −15.64 (s). ^{13}C NMR: δ 145.3, 142.3, 139.9, 136.4, 131.9, 130.8, 130.4, 129.8, 128.5, 127.9, 127.6, 127.4, 127.1, 125.1, 123.2, 24.0. Anal. Calcd for $C_{54}H_{44}P_2$: C, 85.92; H, 5.88. Found: C, 86.11; H, 5.73.

Complex 4. 3 (22 mg, 0.03 mmol) and $PdCl_2(CH_3CN)_2$ (7.8 mg, 0.03 mmol) were dissolved in chloroform (4 mL). The yellow solution was stirred for 10 min at room temperature. All volatiles were evaporated under reduced pressure. The residue was rinsed with diethyl ether and dried in vacuo, affording the product as a yellow powder. ^{1}H NMR ($CDCl_3$): δ 8.51 (s, 1H), 8.04 (m, 4H), 7.53 (t, J = 7.2 Hz, 2H), 7.43 (m, 14H), 7.03 (s, 4H), 2.33 (s, 12H). ^{31}P NMR: δ 19.4. Anal. Calcd for $C_{54}H_{44}P_2Cl_2Pd$: C, 69.57; H, 4.76. Found: C, 69.11; H, 4.82.

Complex 7. 2 (21 mg, 0.03 mmol) and $PdCl_2(CH_3CN)_2$ (7.8 mg, 0.03 mmol) were dissolved in chloroform (4 mL). The yellow solution was stirred for 10 min at room temperature. All volatiles were evaporated under reduced pressure. The residue was rinsed with diethyl ether and dried in vacuo, affording the product as a yellow powder. ^{1}H NMR ($CDCl_3$): δ 8.57 (s, 1H), 8.22 (s, 1H), 8.10 (d, J = 8.4 Hz, 2H), 7.86 (m, 8H), 7.71 (m, 16H), ^{31}P NMR: δ 23.14. Anal. Calcd for $C_{50}H_{36}Cl_2P_2Pd$: C, 68.55; H, 4.14. Found: C, 68.93; H, 3.89.

Complex 5. 3 (22 mg, 0.03 mmol) and $Rh_2Cl_2(CO)_4$ (5.8 mg, 0.015 mmol) were dissolved in dichloromethane (4 mL). The yellow solution was stirred for 10 min at room temperature. All volatiles were evaporated under reduced pressure. The residue was rinsed with diethyl ether and dried in vacuo, affording the product as a yellow powder. ^{1}H NMR ($CDCl_3$): δ 8.51 (s, 1H), 8.04 (d, J = 8.8 Hz, 7H), 7.53 (t, J = 7.2 Hz, 2H), 7.43 (m, 14H), 7.03 (s, 4H), 2.33 (s, 12H). ^{31}P NMR: δ 31.95 (d, J = 96 Hz). Anal. Calcd for $C_{55}H_{44}P_2ClORh$: C, 71.71; H, 4.81. Found: C, 71.93; H, 5.03.

Complex 8. 2 (21 mg, 0.03 mmol) and $Rh_2Cl_2(CO)_4$ (5.8 mg, 0.015 mmol) were dissolved in dichloromethane (4 mL). The yellow solution was stirred for 10 min at room temperature. All volatiles were evaporated under reduced pressure. The residue was rinsed with diethyl ether and dried in vacuo, affording the product as a yellow powder. ^{1}H NMR ($CDCl_3$): δ 8.55 (s, 1H), 8.25 (s, 1H), 8.08 (d, J = 8.4 Hz, 2H), 7.92 (m, 7H), 7.86 (m, 4H), 7.70 (t, J = 5.6 Hz, 3H), 7.58 (m, 19H), ^{31}P NMR: δ 32.55 (d, J = 96 Hz). Anal. Calcd for $C_{55}H_{44}P_2ClORh$: C, 71.71; H, 4.81. Found: C, 71.93; H, 5.03.

Complex 9. 2 (21 mg, 0.03 mmol) and $Rh(COD)_2BF_4$ (12.6 mg, 0.03 mmol) were dissolved in dichloromethane (4 mL). The yellow solution was stirred for 10 min at room temperature. All volatiles were evaporated under reduced pressure. The residue was rinsed with diethyl ether and dried in vacuo, affording the product as a yellow powder. ^{1}H NMR ($CDCl_3$): δ 8.57 (s, 1H), 8.14 (m, 3H),

7.69 (m, 8H), 7.30 (m, 12H), ^{31}P NMR: δ 25.93 (d, $J = 108$ Hz). Anal. Calcd for $C_{58}H_{48}P_2BF_4Rh$: C, 69.90; H, 4.85. Found: C, 70.21; H, 4.99.

Catalytic Experiments. An screw-capped reaction tube was charged with $Pd(OAc)_2$ (0.02 mmol), ligand **2** (0.03 mmol), and K_2CO_3 (2 mmol). The reaction vessel was evacuated and backfilled with N_2 (two times). Through a rubber septum, aryl bromide (1 mmol) and cyclohexene (1.3 mmol) in DMF (3 mL) were added to the reaction tube. The resulting mixture was heated at the indicated temperature for 12 h. After it was cooled to ambient temperature, the reaction mixture was extracted with CH_2Cl_2 and washed with water (three times). The organic layer was dried over $MgSO_4$. After evaporation under reduced pressure, the mixture of products was isolated by means of silica gel column chromatography (hexane) and analyzed by GC.

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Supporting Information Available: CIF files giving crystal data and figures giving ^{1}H, ^{13}C, and ^{31}P NMR spectra for all compounds mentioned in the text. This material is available free of charge via the Internet at http://pubs.acs.org.

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