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[Pd(L)Cl_2]-Catalyzed Selective Hydroxylation of Arylboronic Acids to Phenols

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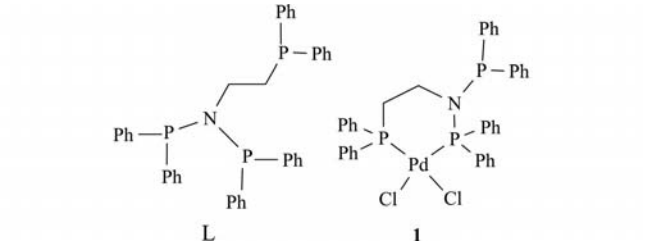
The palladium complex [Pd(L)Cl_2] (**1**) has been prepared by the reaction of Pd(COD)Cl_2 (COD = 1,5-cyclooctadiene) with L [*N*,*N*′-bis(diphenylphosphanyl)-2-(diphenylphosphanyl)-ethanamine]. The ligand L and complex **1** have been characterized by elemental analysis, mass spectrometry and $^1H/^{31}P$ NMR spectroscopy. In the presence of O_2, **1** selectively catalyzes the hydroxylation of a variety of arylboronic acids to the corresponding phenol derivatives in solvents with low-dielectric constants at 298 K, although in solvents with high dielectric constants the same reaction leads to the formation of both phenol and the coupled product, i.e. biaryl. The mechanistic aspects of the selective phenol formation from arylboronic acid with **1** have been addressed.

Introduction

Phenol derivatives are found in natural products such as coal tar, amino acids, flavonoids, tannins and in hormones such as estradiols, estriol and estrone.[1,2] The antioxidant property of phenol makes it an important pharmaceutical material in addition to its utility as a flexible synthetic intermediate.[1] For example, simple phenols are effective disinfectants and 2-methoxyphenol and various polyphenols are found in grapes and wine.[2] Phenol derivatives are traditionally synthesized either by the nucleophilic substitution reaction of activated aryl halides or by the copper-catalyzed transformation of diazoarenes.[3] However, these synthetic procedures involve drastic reaction conditions and they often offer a narrow substrate scope.

The development of relatively facile catalytic routes for the formation of phenol from aryl halides was independently initiated by Hartwig et al.,[4] Buchwald et al.[5] and recently by Beller et al.[6] However, the facile formation of phenol from readily available arylboronic acid derivatives has also recently been established as an efficient route.[7] The direct catalytic hydroxylation of arylboronic acid to phenol by simple copper salts in the presence of a strong base has been reported by Wang et al.[7b] In this regard, phenol formation has also been reported as a side reaction of the palladium-catalyzed Suzuki–Miyaura cross-coupling reaction.[8] In addition, it has been reported that phenol can be generated as a minor product (<20%) along with the major coupling product, biaryl, simply from arylboronic acids using palladium catalysts under an oxidizing environment (air or dioxygen) or in the presence of an oxidizing agent such as copper acetate.[9] The probable mechanism of the homocoupling of arylboronic acid as well as phenol formation as a side product was first reported by Moreno-Mañas et al. using Pd^0 or Pd^{II} catalysts associated with monodentate phosphanes.[9a,9b] This was further extended by Yoshida et al. using Pd$(OAc)_2$ and chelated 1,3-bis(diphenylphosphanyl)propane (dppp).[9c] The detailed mechanistic aspects of these reactions have been reported by Amatore et al.[9d]

In this context the palladium complex **1** has been found to be effective in generating phenol derivatives from a wide variety of arylboronic acids selectively under suitable reaction conditions through an oxidase catalytic pathway.[10]



L 1

This article describes the synthesis and characterization of the ligand L and the corresponding palladium complex **1**. The catalytic aspects of **1** towards the selective hydroxylation of arylboronic acids to their phenol derivatives under suitably designed reaction conditions have been addressed.

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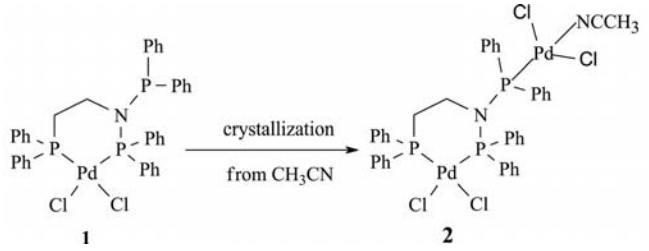
Results and Discussion

Synthesis and Characterization

The preparation of L is given in the Exp. Section. The formation of L has been established by its microanalytical and NMR ($^1H/^{31}P$) spectroscopic data (see Exp. Sect. and Supporting Information) as well as by its single-crystal X-ray structure (see Figure 1 and Tables S1–S2 in the Supporting Information).

Complex **1** was synthesized by the reaction of the precursor complex, $Pd(COD)Cl_2$, and L in CH_2Cl_2 at 298 K and characterized by its microanalytical, solution MS and $^1H/^{31}P$ NMR spectroscopic data (see Exp. Sect. and Figures S1–S3). Single crystals were generated from **1** in a 1:1 CH_3CN/hexane mixture over a period of two weeks. X-ray structure determination revealed a dipalladium species (**2**) where an additional $[PdCl_2(CH_3CN)]$ unit links to the pendant phosphane centre (P2) of the coordinated L (Figure 2 and Tables S1–S2).



This indicates that **1** is transformed to **2** during the slow crystallization process in a coordinating solvent (CH_3CN) possibly according to Equation (1).

$$2PdLCl_2 + CH_3CN \longrightarrow Pd_2LCl_4{\cdot}CH_3CN + L \quad (1)$$
1 **2**

Unfortunately, we were unable to crystallize **1** using other solvents. The bond parameters pertaining to L and **2** (Table S2) match well with those of an analogous molecule containing a diphosphanylamine ligand moiety.[11]

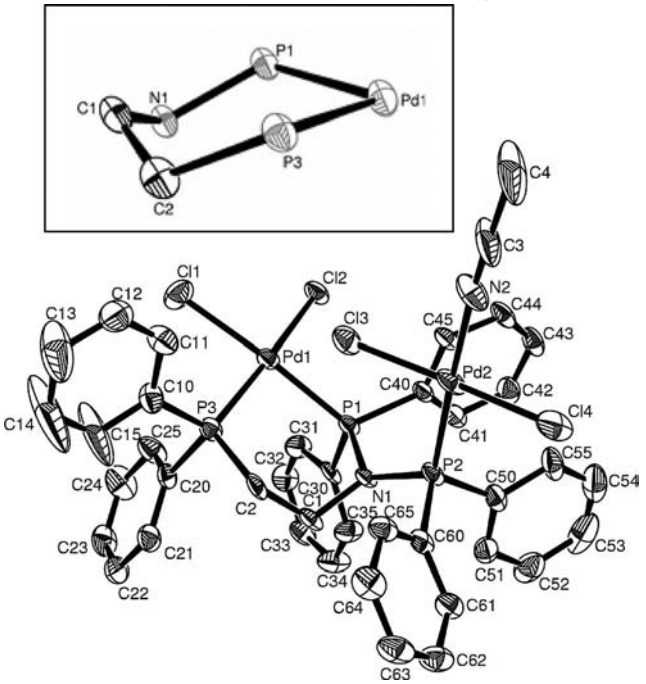


Figure 2. ORTEP diagram of **2**. Ellipsoids are drawn at 50% probability. Hydrogen atoms and solvent molecules are omitted for clarity. Inset is shown the strained chair configuration of the six-membered chelate ring. Selected bond lengths and angles are shown in Table 2.

The mononuclear form of **1** in powdered bulk samples as well as in solution has been established by different experimental techniques. The ^{31}P NMR spectrum of L in $CDCl_3$ exhibits two signals at 60.60 and –21.8 ppm corresponding to P1/P2 and P3, respectively (Figure S2a). However, the ^{31}P NMR spectrum of **1** in $(CD_3)_2SO$ shows three magnetically nonequivalent phosphane signals at 74.10

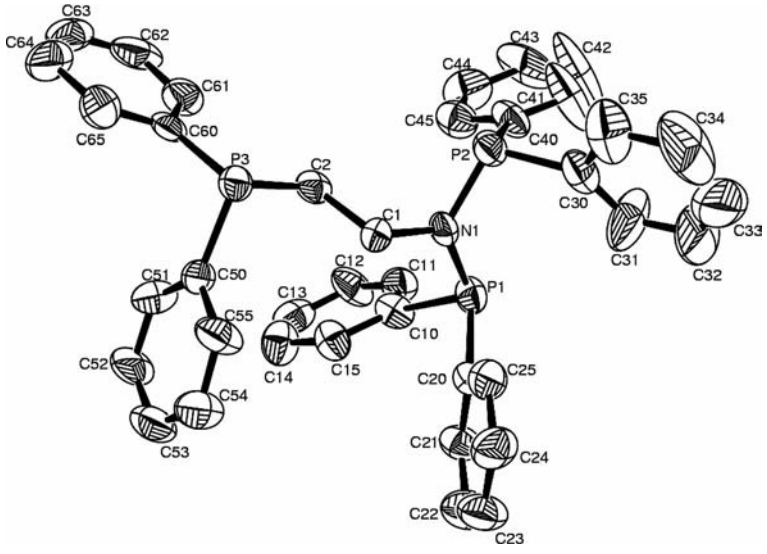
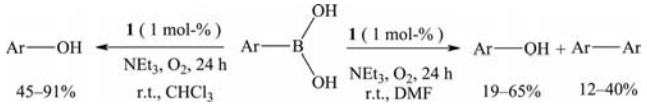


Figure 1. ORTEP diagram of L. Ellipsoids are drawn at 50% probability. Hydrogen atoms are omitted for clarity. Selected bond lengths and angles are shown in Table 2.

(P1), 56.2 (P2) and 19.01 (P3) ppm. The chemical shifts of two of the phosphane signals (P1 and P3) in **1** are significantly shifted compared to L, whereas the chemical shift of the pendant phosphane (P2) remains almost unaltered (Figure S2b). This suggests that two out of three phosphane centres in L are coordinated to the metal ion leaving the third phosphane uncoordinated as expected for monopalladated **1**. The ESI mass spectrum of **1** shows the molecular ion peak at *m*/*z* 737.81 corresponding to PdLCl (calculated mass: 738.06) rather than the full molecule $PdLCl_2$ (calculated mass: 773.56), which implies the lability of one of the Cl ligands in **1**. Consequently, the isotopic pattern of palladium in the mass spectrum matches well with the mononuclear nature of **1** (Figure S3). The single irreversible oxidation process observed with E_{pa} at 1.2 V vs. SCE in acetonitrile further justifies the existence of the monopalladated form of **1** in the bulk sample (Figure S4).

Catalytic Study

The catalytic activity of freshly prepared **1** with phenylboronic acid under an oxidizing (O_2) environment is summarized in Scheme 1. The selective formation of phenol as an exclusive product in solvents with low dielectric constants (Table 1) is of special interest. Conversely, the same reaction in solvents with high dielectric constants results in a coupled product, biphenyl, along with the hydroxylated product, phenol (Table 1).



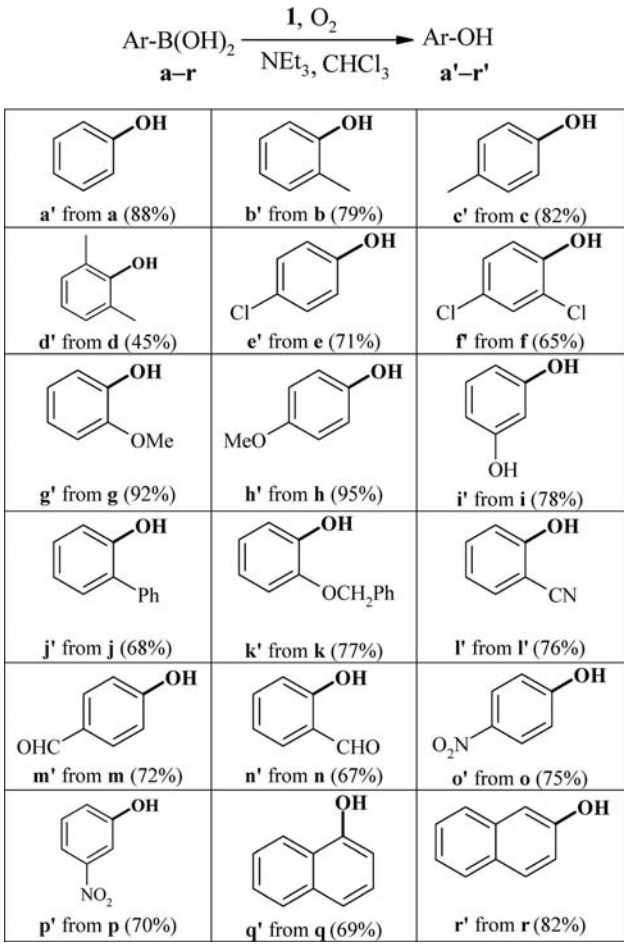
Scheme 1. Generalized reaction scheme.

Table 1. Catalytic activities of **1** in different solvents using phenylboronic acid as substrate.

Solvent (ε)	Yield [%] O_2 PhOH	Ph-Ph	Air PhOH	Ph-Ph	N_2
Toluene (2.37)	52	0	42	0	0
$CHCl_3$ (4.7)	88	0	66	0	0
CH_2Cl_2 (8.93)	75	0	65	0	0
EtOH (24.85)	36	34	28	27	0
CH_3CN (35.688)	46	24	52	20	0
DMF (37.22)	28	40	25	35	0
DMA (37.78)	30	35	23	32	0

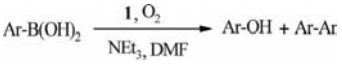
In order to establish the general applicability of the catalytic process as stated in Scheme 1, a wide variety of arylboronic acid substrates, **a**–**r**, have been tested in $CHCl_3$, a solvent of low dielectric constant. For all the arylboronic acids chosen, the same trend of exclusive formation of corresponding phenol derivatives is observed. This implies that the reactions proceed with complete functional group tolerance (Table 2). The presence of electron-donating (such as OMe) or -withdrawing groups (such as Cl) in the framework of the arylboronic acid increases or decreases the yield of the phenol product, respectively.

Table 2. Oxidative hydroxylation of arylboronic acid by **1** in $CHCl_3$.

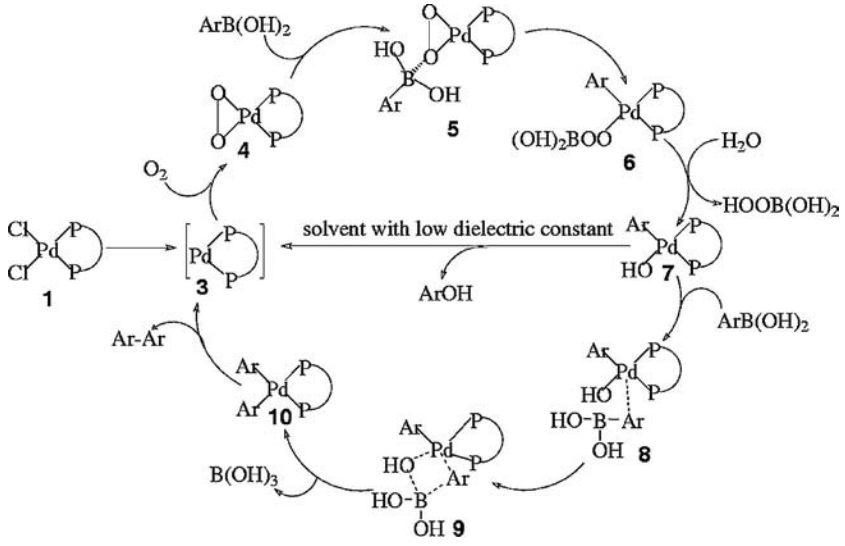


The reaction has also been tested in a solvent with a high dielectric constant (DMF) using selected arylboronic acid substrates, and, in all cases, both phenol and biaryl are formed (Table 3). However, using 1-naphthylboronic acid as the substrate (**q**), led to the yield of the coupled product,

Table 3. Catalytic results on oxidative coupling of arylboronic acid catalyzed by **1** in DMF with representative substrates.



Substrate	Yield [%] Ar–OH	Ar–Ar
a	28 (**a′**)	40 (**a′′**)
b	27 (**b′**)	32 (**b′′**)
c	25 (**c′**)	35 (**c′′**)
e	19 (**e′**)	32 (**e′′**)
f	19 (**f′′**)	27 (**f′′**)
g	21 (**g′**)	40 (**g′′**)
h	23 (**h′**)	39 (**h′′**)
i	21 (**i′**)	25 (**i′′**)
k	27 (**k′**)	21 (**k′′**)
m	12 (**m′**)	30 (**m′′**)
q	65 (**q′**)	12 (**q′′**)



Scheme 2. Proposed catalytic cycle.

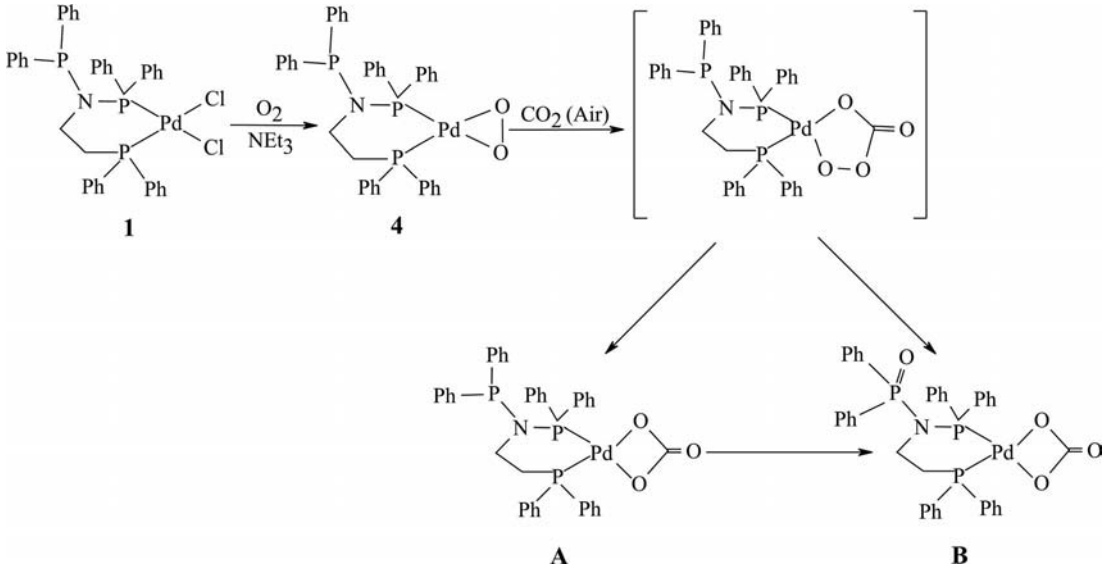
binaphthyl (**q′′**), being reduced drastically in DMF as the bulkier naphthyl group retards the rate of the reductive elimination process (Scheme 2).

Mechanistic Outlook

Control reactions of arylboronic acid in $CHCl_3$ and DMF (i) with **1** under N_2 and (ii) in the absence of **1** under O_2 failed to give any products implying the necessity of both **1** and O_2 to facilitate the reactions in Scheme 1. This also suggests that the reactions in Scheme 1 are initiated through the formation of a reactive palladium–peroxo species.[9d,12] The involvement of the palladium–peroxo species (**4**) in the catalytic cycle (Scheme 2) has been evidenced by ESI-MS (Figure S5), ^{1}H NMR spectroscopy (Figure S6) and cyclic voltammetry (Figure S4).

The addition of NEt_3 to the yellow solution of **1** under oxygen causes the spontaneous formation of a short-lived red solution that further changes to a straw-yellow solution with time.[13a] The ESI-MS of the in situ generated solution in degassed CH_3CN exhibits an ion peak at *m*/*z* 734.96 corresponding to $PdLO_2$ (**4**) (calculated mass: 735.08, Figure S5). Consequently, the proton signals of **4** in its ^{1}H NMR spectrum are slightly shifted compared to those of **1** (Figure S6) and it exhibits an irreversible oxidation process at E_{pa} 0.98 V vs. SCE in CH_3CN which is about 200 mV less than that of **1** (Figure S4).

However, on exposure to air, the solution of **4** transforms to a mixture of stable carbonate species (**A**/**B**) from the involvement of aerial CO_2 (Scheme 3). The reaction of metal–peroxo complexes with CO_2 to give peroxycarbonato species and their subsequent facile conversion to carbonato



Scheme 3. Possible pathways for the reaction of **1** with O_2 in the absence of arylboronic acid.

species is well documented.[13] The time-monitored ^{31}P NMR spectroscopic data in Table 4 also reveal the presence of a new peak at 29.4 ppm in addition to the three original ^{31}P signals for **1**, which indicates that uncoordinated phosphane (P2) is oxidized to O=P(2) in the oxidizing reaction environment (Figure S7). With time, the peak that corresponds to uncoordinated P(2) (δ = 54.0 ppm) decreases in intensity and after 24 h it completely vanishes and the new peak at 29.4 ppm due to O=P(2) remains intact. This indicates the gradual dominance of **B** with time as shown in Scheme 3. The slight change in the chemical shifts in the ^{31}P NMR spectrum with time compared to those of **1** implies the immediate change in chemical environment around the palladium in **A** and **B**. The IR spectrum (Figure S8) of the crude solid product shows additional bands near 565, 1123 and 1652 cm^{-1} corresponding to Pd–O, P=O and C=O stretching frequencies, respectively, that could be attributed to **B** in Scheme 3.[13]

Table 4. ^{31}P NMR spectroscopic data of L and **1**, and time-monitored data of **1** in the presence of NEt_3 in $(CD_3)_2SO$.

Species	δ ppm (P*n*)
L	60.6 (P1 & P2), –21.8 (P3)
1	74.2 (P1), 56.3 (P2), 19.01 (P3)
(1 + NEt_3) in 0 h	79.25 (P1), 54.0 (P2), 22.46 (P3), 29.4 (O=P2)
(1 + NEt_3) in 6 h	79.25 (P1), 54.0 (P2), 21.82 (P3), 29.4 (O=P2)
(1 + NEt_3) in 18 h	79.27 (P1), 54.02 (P2), 21.88 (P3), 29.4 (O=P2)
(1 + NEt_3) in 24 h	79.26 (P1), 22.46 (P3), 29.4 (O=P2)

The ^1H NMR spectrum of the in situ generated species from **4** and *p*-tolylboronic acid (**c**, Table 2) is different from those of independent **4**, **c**, **c′** and **c′′** (**c′** = *p*-tolylphenol, **c′′** = 4,4′-dimethylbiphenyl). Two new doublets in the region of 6.5–6.9 ppm corresponding to the formation of an arylpalladium(II) species (steps **6**–**7** in Scheme 2)[9d] are observed, which disappear with time (Figure S9). The disappearance of broad signal of **c** at 29.6 ppm in the ^{11}B NMR spectrum (Figure S10) is also indicative of the transformation of **5** to **7** in Scheme 2.[9d,14] The instantaneous shifting of potential from 0.90 V (vs. SCE) of **4** to 0.85 V (vs. SCE) on addition of **c** to **4** in CH_3CN also provides indirect support for this transformation (Figure S4).

Phenol is considered to be generated from **7** by reductive elimination of the Ar and OH groups on palladium. Such palladium catalyzed direct reductive elimination towards the formation of phenol at room temp. has been reported by Beller et al.,[6b] and is considered as a bottle-neck step of the reaction. The water involved in the catalytic cycle between **6** and **7** may result from the formation of boroxine from arylboronic acid.[9d–9e,14]

It has been proposed that minor amounts of phenol are formed during the palladium-catalyzed oxidative process of arylboronic acid outside the catalytic cycle by the reaction of arylboronic acid with H_2O_2, a hydrolysis product of peroxyboronic acid.[9d] However, the same route seems to be nonoperational in this case as the use of methyl *p*-tolyl sulfide and dimethyl sulfide in the place of arylboronic acid (Scheme 1) failed to give sulfoxide and/or sulfone, the expected products if H_2O_2 plays a significant role in the formation of phenol.[15] This indicates that the formation of a large quantity of phenol is unlikely to proceed through the noncatalytic pathway. Therefore, it may be logical to assume that peroxyboronic acid is eliminated as $2\,HOOB(OH)_2 \rightarrow 2\,B(OH)_3 + O_2$.

Inspection of the product distribution in Table 2 reveals the decrease in phenol formation in the presence of a substituent in the *ortho*-position of the aryl group of arylboronic acid [such as **b** (Me) and **j** (Ph)]. The yield of phenol decreases drastically with substrate **d** where both the *ortho*-positions are blocked by Me groups. Moreover, the yield of phenol formation increases with the activated substrates such as OMe in the aryl ring of boronic acid (**g** and **h** in Table 2). These collectively justify the formation of phenol through the reductive elimination of the Ar and OH groups from **7** as shown in Scheme 2. Similar reductive elimination-mediated palladium-catalyzed C–O,[16,17] C–N[16–18] and C–S[16–19] coupling processes are known.

The formation of the coupled product, biaryl, in addition to phenol in DMF is considered to take place through transmetallation (**8**, **9** in Scheme 2) followed by reductive elimination (**10** in Scheme 2) pathways as a part of the same catalytic cycle[20] instead of two independent routes. The following control experiments provide the necessary justification for this mechanism. In the presence of two different boronic acids, **a** and **c** in a 1:1 ratio (**1**:**a**:**c** = 1:77.5:77.5) in DMF only the corresponding phenols (**a′** and **c′**) are formed. Even when the catalyst amount is doubled and the ratio is changed to 1:38.75:38.75 only phenol formation is observed. Formations of biaryls are observed only on doubling the catalyst amount further to a ratio of 1:19.375:19.375 (Table 5). This implies that after initial formation of phenol the coupled products start to form. At a lower ratio of **1**, boronic acid coupled products are not formed as the catalyst is consumed in the initial phenol formation process. The formation of heterocoupled products along with the corresponding homocoupled products in Table 5 provides experimental justification for the reductive elimination for biaryl formation. In the ESI-MS, a peak at *m*/*z* 857.01, corresponding to $PdLPh_2$ (calculated mass: 857.14), provides direct evidence for the involvement of **10** (Scheme 2) in the catalytic cycle, which was observed upon addition of two equivalents of phenylboronic acid (**a**) to the in situ generated solution of **4** (Figure S11).[20,21]

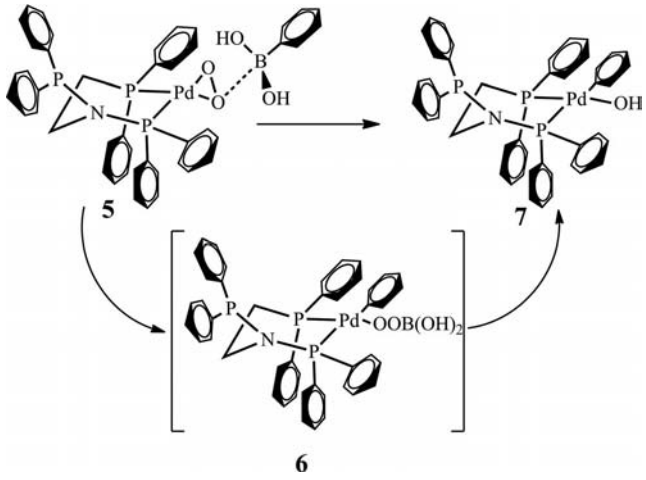
Table 5. Catalytic study on mixed substrates.[a]

Substrates	**1**:**a**:**c**	Product distribution ratio[b] [%] under O_2				
		PhOH	ArOH	Ar-Ar	Ph-Ph	Ar-Ph
a + **c**	1:77.5:77.5	36	64	0	0	0
	1:38.75:38.75	36	64	0	0	0
	1:19.37:19.37	44	45	5	4	2

[a] Experimental conditions: catalyst **1** (5 mg, 0.0065 mmol), phenylboronic acid (**a**) and *p*-tolylboronic acid (**c**) with respective ratios were taken up in solvent (5 mL) along with freshly distilled NEt_3 (2 mg, 0.02 mmol). The resultant reaction mixture was stirred for 24 h at 298 K under bubbling O_2 and the reaction was monitored by GC. In each case an authenticated sample was used to standardize the GC experiments. [b] Based on GC response.

Effect of Ligand and Solvent

In previous reports of palladium-catalyzed coupling of arylboronic acids to biaryls, phenol was detected as a minor product (<20%).[9] As listed in Table S3, palladium catalysts involving both chelating and nonchelating ligands are generally less effective in producing phenol selectively from arylboronic acid.[9] Among them, the palladium catalysts incorporating chelated diphosphane ligands such as dppp (Entry 11, Table S3),[9c] dppe [1,2-bis(diphenylphosphanyl)-ethane] (Entry 12, Table S3) and dppf [1,1′-bis(diphenylphosphanyl)ferrocene] (Entry 13, Table S3) generate biaryl instead of phenol. It is therefore apparent that the ligand L in **1** facilitates the reductive elimination step (Scheme 2, **7** to **3**) for the preferential formation of phenol. This is possibly due to the advantage of the presence of the pendant $N(PPh_2)$ unit to the molecular framework of coordinated L in **1**, which in turn introduces the additional stability of the six-membered chelate ring throughout the catalytic cycle as evidenced by NMR spectra and no hemilability is observed spectroscopically.[22] The six-membered ring in **1** has been stabilized in an appreciably strained chair conformation and sp^3 N1 is in a planar configuration with the adjacent C1 and P1 (inset in Figure 2 and Table S2) probably due to strong pπ(N)–dπ(P) back bonding, which is also reflected in free L (Figure 1 and Table S2). The stable but strained and sterically crowded chelate ring arising from L in one side of the palladium in **1** makes the other side of the catalyst more accessible to nucleophilic attack within the catalytic cycle leading to the formation of **7** from **5** as evidenced by ^1H NMR spectroscopy (Scheme 4 and Figure S9).



Scheme 4. Proposed route for reductive elimination leading to phenol formation.

In this case the transmetallation step occurs only in solvents with a high dielectric constant without the involvement of base. This proceeds through the cleavage of the Pd–O bond in **7** in order to form the new $Pd–C_{Ar}$ bond. Although it was previously believed that transmetallation can occur only in the presence of a base, recent studies have also shown that transmetallation can also occur in the absence of a base.[20,23] In view of this, it has been proposed that transmetallation proceeds by a four-membered transition state (**9** in Scheme 2) with the concomitant elimination of $B(OH)_3$.[20,23]

It should be noted that the transmetallation step is a less understood and more energy demanding step even in a Suzuki–Miyaura coupling reaction.[20,23a,23b] A high dielectric solvent with coordinating ability is known to increase the rate of a base-free transmetallation step.[20,23f] Our observation of facile biaryl formation in solvents with high dielectric constants is therefore consistent with these literature reports.[20]

Conclusions

This work demonstrates a generalized reaction scheme (Scheme 1, Table 2) for the selective formation of phenol derivatives from a wide variety of arylboronic acids in an oxidizing environment catalyzed by **1**, which incorporates an unsymmetrical chelating phosphane-based ligand. Control experiments and other experimental evidence are in agreement with the initial formation of a palladium–peroxo species, and the phenol formation takes place through the reductive elimination step as shown in Scheme 2.

Experimental Section

Materials and Instrumentations: Manipulations and preparations were performed using standard Schlenk techniques in oven-dried glassware under an atmosphere of nitrogen, wherever required. Solvents were dried by standard procedures, distilled under nitrogen and used immediately. Triethylamine was heated to reflux with calcium hydride before distillation and stored over potassium hydroxide. Palladium chloride and triethylamine were obtained from SD Fine, India. All other reagents and chemicals were obtained from Aldrich, USA and used as received. Oxygen and nitrogen gases were supplied by BOC, India and all the solvents were purchased from Merck India. Column chromatography was carried out using silica gel, 60–120 mesh from Merck India and TLC experiments were performed using Merck silica gel 60 F_{254} precoated sheets and visualized by UV (254 nm). $Pd(dppe)Cl_2$,[11d] $Pd(dppf)Cl_2$[11e] and $Pd(COD)Cl_2$[24] were prepared according to literature procedures.

^1H and ^{31}P NMR spectra were recorded with 300 MHz Varian and 300 MHz Bruker spectrometers. Chemical shift data are quoted as δ in ppm and s, d, dd, t, q, sx and m represent singlet, doublet, doublet of doublet, triplet, quartet, sextet and multiplet, respectively. IR spectra were measured using a Thermo Nicolet 320 FTIR spectrophotometer. ESI-mass spectra were recorded with a Micromass Q-ToF mass spectrometer. Elemental analyzes were carried out with a Perkin–Elmer 240C elemental analyser. Cyclic voltammetry studies were carried out using a PAR model 273A electrochemistry system. Platinum wire working and auxiliary electrodes and an aqueous SCE were used in a three-electrode configuration. The supporting electrolyte was 0.1 M $[NEt_4][ClO_4]$ and the solute concentration was ca. 10^{-3} M. Reactions were monitored by gas chromatography with a FID detector (Shimadzu GC-2014 gas chromatograph) using a capillary column (112-2562 CYCLODEXB, from J&W Scientific, length 60 m, inner diameter 0.25 mm, film 0.25 μm).

Synthesis of L: In a two-necked round-bottomed flask, chlorodiphenylphosphane (1.8 mL, 9.61 mmol) was dissolved in dry dichlo-

romethane (35 mL) and distilled triethylamine (5 mg) was added under nitrogen. A solution of 2-(diphenylphosphanyl)ethylamine (4.367 mmol, 1 g) in dry dichloromethane (10 mL) was added drop wise to the solution of chlorodiphenylphosphane at 0 °C over 20 min under nitrogen. The stirring was allowed to continue for another 10 min at 0 °C. The solution was then allowed to stir for next 16 h at room temp., and crystalline triethylammoniumhydrochloride precipitated out. The solution was filtered and the filtrate was evaporated to dryness. The gummy solid obtained was dissolved in minimum volume of distilled hot ethanol and allowed to cool inside a refrigerator overnight. The crystalline mass was collected by filtration and dried under vacuum (Yield: 5.3 g, 80%). The ligand was characterized by single-crystal X-ray diffraction (Figure 1) and ^{1}H (Figure S1a) and ^{31}P NMR spectroscopy (Figure S2a). $C_{38}H_{34}NP_3$ (597.1904): calcd. C 76.36, H 5.74, N 2.34; found C 76.21, H 5.70, N 2.21. ^{1}H NMR ($CDCl_3$, 300 MHz): δ = 7.10–7.36 (m, 30 H, Ph–H), 3.37–3.42 (sx, 2 H, H_2C–PPh_2), 1.55 [t, 2 H, H_2C–N(PPh_2)$_2$] ppm. ^{31}P NMR ($CDCl_3$, 300 MHz, δ [ppm]): –21.802 [s, 1P, H_2C–*P(3)*Ph_2], 60.605 [s, 2P, H_2C–N{*P(1,2)*Ph_2}$_2$] ppm. IR (KBr): $\tilde{\nu}$ = 2924, 2853, 3068, 3049, 1584, 1478, 1433, 1091, 1054, 842, 740 cm^{-1}.

Synthesis of 1: To a solution of L (50 mg, 0.084 mmol) in dichloromethane (10 mL) in a two-necked round-bottomed flask was added dropwise Pd(COD)Cl_2 (22 mg, 0.078 mmol) in dichloromethane (5 mL) over 10 min under nitrogen. The transparent yellow solution was stirred for 6 h. The solution was then concentrated (ca. 2–3 mL) under reduced pressure and diethyl ether was added to precipitate the yellow complex. It was allowed to stand overnight inside the refrigerator for complete precipitation. The product was collected by filtration, washed with diethyl ether and dried under vacuum. $C_{38}H_{34}Cl_2NP_3Pd$ (773.0316): calcd. C 58.99, H 4.40, N 1.69; found C 58.76, H 4.43, N 1.71. ^{1}H NMR [$(CD_3)_2SO$, 300 MHz]: δ = 6.9–7.9 (m, 30 H, Ph–H), 3.1–3.2 (sx, 2 H, H_2C–PPh_2), 1.8 [t, 2 H, H_2C–N(PPh_2)$_2$] ppm. ^{31}P NMR [$(CD_3)_2SO$, 300 MHz (ppm)]: δ = 19.015 [s, 1 P, H_2C–*P(3)*Ph_2–Pd], 56.2 [d, 1 P, H_2C–N*P(2)*Ph_2], 74.10 [dd, 1 P, Pd–*P(1)*Ph_2–N] ppm. IR (KBr): $\tilde{\nu}$ = 3053, 2921, 2854, 1629, 1434, 1183, 1099, 1077, 997, 825, 744, 714, 690, 513 cm^{-1}.

Catalytic Experiments: Catalyst **1** (5 mg, 0.0065 mmol) and arylboronic acid (0.65 mmol) were dissolved in solvent (5 mL) along with freshly distilled NEt_3 (2 mg, 0.02 mmol). The resultant reaction mixture was stirred for 24 h at 298 K either under bubbling of O_2 or air through the mixture. The progress of each reaction was monitored by GC. In each case authenticated samples were used to standardize the GC experiments. The solvent was removed under reduced pressure after each reaction and the product was passed through a silica gel (60–120 mesh) column using hexane/ethyl acetate as the eluent. In case of more than one product, further separation was performed on a preparatory TLC plate using a hexane/petroleum ether–ethyl acetate mixture. On removal of the solvent under reduced pressure pure products were obtained in each case and the isolated products were used to calculate the yield. The formation of pure products were further confirmed by ^{1}H NMR spectroscopy. All the reactions were carried out three times to establish the reproducibility and reliability of the results.

Crystallographic Details: Single crystals of L (Figure 1) and **2** (Figure 2) were grown by slow evaporation of 1:1 acetonitrile/hexane solutions of L and **1** at 298 K. Single-crystal X-ray diffraction data were collected using an OXFORD XCALIBUR-S CCD single-crystal X-ray diffractometer at 150 K. The structures were solved and refined by full-matrix least-squares techniques on F^2 using the SHELX-97 program.[25] All data were corrected for Lorentz polarization and absorption effects, and the non-hydrogen atoms were refined anisotropically. Hydrogen atoms were included in the refinement process as per the riding model. The crystal of **2** contains one normal CH_3CN molecule and one disordered CH_3CN molecule as solvent of crystallization. Important crystallographic details and selected bond lengths and angles are listed in Tables S1 and Table S2, respectively.

CCDC-773831 (for L) and -773832 (for **2**) contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

Supporting Information (see footnote on the first page of this article): X-ray parameters, product distribution in different palladium-catalyzed reactions, characterization of ligand L, catalyst **1**, intermediates, different substituted phenols, and substituted biphenyls.

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[1] a) Z. Rappoport, *The Chemistry of Phenols*, Wiley-VCH, Weinheim, Germany, **2003**; b) J. H. Tyman, *Synthetic and Natural Phenols*, Elsevier, New York, **1996**.
[2] G. J. Soleas, E. P. Diamandis, D. M. Goldberg, *J. Clin. Lab. Anal.* **1997**, *11*, 87–93, and references cited therein.
[3] a) C. Hoarau, T. R. R. Pettus, *Synlett* **2003**, 127–137; b) P. Hanson, J. R. Jones, A. B. Taylor, P. H. Walton, A. W. Timms, *J. Chem. Soc. Perkin Trans. 2* **2002**, 135–140; c) T. George, R. Mabon, G. Sweeney, J. B. Sweeney, J. Tavassoli, *J. Chem. Soc. Perkin Trans. 1* **2000**, 2529–2574, and references cited therein; d) D. A. Whiting, in: *Comprehensive Organic Chemistry. The Synthesis and Reactions of Organic Compounds* (Eds.: D. Barton, W. D. Ollis), Pergamon Press, Oxford, **1979**, vol. 1; e) M. C. Willis, *Angew. Chem. Int. Ed.* **2007**, *46*, 3402–3404.
[4] S. Mann, C. Incarvito, A. L. Rheingold, J. F. Hartwig, *J. Am. Chem. Soc.* **1999**, *121*, 3224–3225.
[5] K. W. Anderson, T. Ikawa, R. E. Tundel, S. L. Buchwald, *J. Am. Chem. Soc.***2006**, *128*, 10694–10695.
[6] a) T. Schulz, C. Torborg, B. Schäffner, J. Huang, A. Zapf, R. Kadyrov, A. Börner, M. Beller, *Angew. Chem. Int. Ed.* **2009**, *48*, 917–922; b) A. G. Sergeev, T. Schulz, C. Torborg, A. Spannenberg, H. Neumann, M. Beller, *Angew. Chem. Int. Ed.* **2009**, *48*, 7595–7599.
[7] a) K. Hosoi, Y. Kuriyama, S. Inagi, T. Fuchigami, *Chem. Commun.* **2010**, *46*, 284–286; b) J. Xu, X. Wang, C. Shao, D. Su, G. Cheng, Y. Hu, *Org. Lett.* **2010**, *12*, 1964–1967, and references cited therein; c) E. Kianmehr, M. Yahyaee, K. Tabatabai, *Tetrahedron Lett.* **2007**, *48*, 2713–2715; d) G. K. S. Prakash, S. Chacko, C. Panja, T. E. Thomas, L. Gurung, G. Rasul, T. Mathew, G. A. Olaha, *Adv. Synth. Catal.* **2009**, *351*, 1567–1574; e) J. Simon, S. Salzbrunn, G. K. S. Prakash, N. A. Petasis, G. A. Olah, *J. Org. Chem.* **2001**, *66*, 633–634.
[8] a) A. Suzuki, in: *Metal-Catalyzed Cross Coupling Reactions* (Eds.: F. Diederich, P. J. Stang), Wiley-VCH, Weinheim, Germany, **1998**, p. 49; b) E. M. Campi, W. R. Jackson, S. M. Marcuccio, C. G. M. Naeslund, *J. Chem. Soc., Chem. Commun.* **1994**, 2395–2396; c) T. Gillmann, T. Weeber, *Synlett* **1994**, 649–650; d) Z. Z. Song, H. N. C. Wong, *J. Org. Chem.* **1994**, *59*, 33–41.

[9] a) M. Moreno-Mañas, M. Perez, R. F. Pleixats, *J. Org. Chem.* **1996**, *61*, 2346–2351; b) M. A. Aramendia, M. Lafont, M. Moreno-Mañas, M. Perez, R. Pleixats, *J. Org. Chem.* **1999**, *64*, 3592–3594; c) H. Yoshida, Y. Yamaryo, J. Ohshita, A. Kunai, *Tetrahedron Lett.* **2003**, *44*, 1541–1544; d) C. Adamo, C. Amatore, I. Ciofini, A. Jutand, H. Lakmini, *J. Am. Chem. Soc.* **2006**, *128*, 6829–6836, and references cited therein; e) H. Lakmini, I. Ciofini, A. Jutand, C. Amatore, C. Adamo, *J. Phys. Chem. A* **2008**, *112*, 12896; f) G. W. Kabalka, L. Wang, *Tetrahedron Lett.* **2002**, *43*, 3067–3069; g) M. S. Wong, X. L. Zhang, *Tetrahedron Lett.* **2001**, *42*, 4087–4089; h) K. A. Smith, E. M. Campi, W. R. Jackson, S. Marcuccio, C. G. M. Naeslund, G. B. Deacon, *Synlett* **1997**, 131–132; i) Y. Yamamoto, *Synlett* **2007**, 1913–1916; j) S. Punna, D. D. Diaz, M. G. Finn, *Synlett* **2004**, 2351; k) Z. Xu, J. Mao, Y. Zhang, *Catal. Commun.* **2008**, *9*, 97–100; l) J. S. Yadav, K. U. Gayathri, H. Ather, H. Rehman, A. R. Prasad, *J. Mol. Catal. A* **2007**, *271*, 25–27; m) J. S. Chen, K. K. Jespersen, J. G. Khinast, *J. Mol. Catal. A* **2008**, *285*, 14–19; n) D. G. Hall, in: *Boronic Acids Preparation, Applications in Organic Synthesis and Medicine* (Ed.: D. G. Hall), Wiley-VCH, Weinheim, Germany, **2005**, p. 231.

[10] a) S. S. Stahl, *Science* **2005**, *309*, 1824–1826; b) K. M. Gligorich, M. S. Sigman, *Angew. Chem. Int. Ed.* **2006**, *45*, 6612–6615.

[11] a) T. Fanjul, G. Eastham, N. Fey, A. Hamilton, A. G. Orpen, P. G. Pringle, M. Waugh, *Organometallics* **2010**, *29*, 2292–2305; b) D. J. Schaffer, A. S. Batsanov, C. M. Jensen, S. Takara, *Polyhedron* **2010**, *29*, 1660–1666; c) A. G. Sergeev, H. Neumann, A. Spannenberg, M. Beller, *Organometallics* **2010**, *29*, 3368–3373; d) W. L. Steffen, G. J. Palenik, *Inorg. Chem.* **1976**, *15*, 2432–2439; e) I. R. Butler, W. R. Cullen, T. Kim, S. J. Rettig, J. Trotter, *Organometallics* **1985**, *4*, 972–980; f) Z. Fei, W. H. Ang, D. Zhao, R. Scopelliti, P. J. Dyson, *Inorg. Chim. Acta* **2006**, *359*, 2635–2643; g) I. Bachert, P. Braunstein, M. K. McCart, F. F. de Biani, F. Laschi, P. Zanello, G. Kickelbick, U. Schubert, *J. Organomet. Chem.* **1999**, *573*, 47–59; h) I. Bachert, I. Bartusseck, P. Braunstein, E. Guillon, J. Rosé, G. Kickelbick, *J. Organomet. Chem.* **1999**, *580*, 257–264; i) P. Braunstein, H. P. Kormann, M. Z. Wolfgang, R. Pugin, G. Schmid, *Chem. Eur. J.* **2000**, *6*, 4637–4646.

[12] a) R. A. Sheldon, J. K. Kochi, *Metal-catalyzed Oxidations of Organic Compounds*, Academic Press, New York, **1981**, chapter 4; b) K. M. Gligorich, M. S. Sigman, *Chem. Commun.* **2009**, 3854–3867.

[13] a) M. Yamashita, K. Goto, T. Kawashima, *J. Am. Chem. Soc.* **2005**, *127*, 7294–7295; b) J. S. Valentine, *Chem. Rev.* **1973**, *73*, 235–245.

[14] a) All the boronic acids and active catalysts are completely soluble in $CHCl_3$ and DMF under the experimental conditions: b) M. F. Lappert, *Chem. Rev.* **1956**, *56*, 959–1064.

[15] a) K. P. Bryliakov, E. P. Talsi, *Eur. J. Org. Chem.* **2008**, 3369–3376; b) M. Mba, L. J. Prins, G. Licini, *Org. Lett.* **2007**, *9*, 21–24.

[16] a) J. F. Hartwig, *Nature* **2008**, *455*, 314–322; J. F. Hartwig, *Acc. Chem. Res.* **2008**, *41*, 1534–1544; J. F. Hartwig, *Acc. Chem. Res.* **1998**, *31*, 852–860; b) A. R. Muci, S. L. Buchwald, *Top. Curr. Chem.* **2002**, *219*, 131–209; c) J. F. Hartwig, in: *Handbook of Organopalladium Chemistry for Organic Synthesis* (Ed.: E. I. Negishi), Wiley-Interscience, **2002**, vol. 1.

[17] M. Palucki, J. P. Wolfe, S. L. Buchwald, *J. Am. Chem. Soc.* **1997**, *119*, 3395–3396.

[18] B. P. Fors, S. L. Buchwald, *J. Am. Chem. Soc.* **2009**, *131*, 12898–12899.

[19] G. Mann, D. Baranano, J. F. Hartwig, A. L. Rheingold, I. A. Guzei, *J. Am. Chem. Soc.* **1998**, *120*, 9205–9219.

[20] C. Amatore, A. Jutand, G. L. Duc, *Chem. Eur. J.* **2011**, *17*, 2492–2503.

[21] A. O. Aliprantis, J. W. Canary, *J. Am. Chem. Soc.* **1994**, *116*, 6985–6986.

[22] a) Z. Weng, S. Teo, T. S. A. Hor, *Acc. Chem. Res.* **2007**, *40*, 676–684; b) M. Bassetti, *Eur. J. Inorg. Chem.* **2006**, 4473–4482; c) J. W. Faller, S. C. Milheiro, J. Parr, *J. Organomet. Chem.* **2008**, *693*, 1478–1493.

[23] a) A. A. C. Braga, N. H. Morgon, G. Ujaque, F. Maseras, *J. Am. Chem. Soc.* **2005**, *127*, 9298–9307; b) Y. Huang, C. M. Weng, F.-E. Hong, *Chem. Eur. J.* **2008**, *14*, 4426–4434; c) M. Sumimoto, N. Iwane, T. Takahama, S. Sakaki, *J. Am. Chem. Soc.* **2004**, *126*, 10457–10471; d) J. Jover, N. Fey, M. Purdie, G. C. Lloyd-Jones, J. N. Harvey, *J. Mol. Catal. A* **2010**, *324*, 39–47; e) A. A. C. Braga, N. H. Morgon, G. Ujaque, A. Lledó, F. Maseras, *J. Organomet. Chem.* **2006**, *691*, 4459–4466; f) B. Crociani, S. Antonaroli, L. Canovese, P. Uguagliati, F. Visentin, *Eur. J. Inorg. Chem.* **2004**, 732–742.

[24] D. Drew, J. R. Doyle, *Inorg. Synth.* **1972**, *13*, 52.

[25] G. M. Sheldrick, SHELX-97, *Program for Crystal Structure Solution and Refinement, University of Göttingen*, Göttingen, Germany, **1997**.

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