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Article

Synthesis and Characterization in Solution and in the Solid State of the Palladium Aryl Bromide Complexes [Pd(Ar)Br{(S)-BINAP}]. Formation of Cyclopalladated Complexes and Direct Observation of a C-N Reductive Elimination To Form Heterocycles

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As reações de uma mistura $[Pd_2(dba)_3]$/P(*o*-tolyl)$_3$ (1/4) com brometos de arila orto substituídos conduziram aos dímeros $[Pd(Ar)(\mu\text{-}Br)\{P(o\text{-tolyl})_3\}]_2$ que, após adição de 2 equiv. de (S)-BINAP formaram os complexos $[PdBr(o\text{-}RC_6H_4)\{(S)\text{-BINAP}\}]$ em bons rendimentos (57-89%). A estrutura molecular do complexo $[PdBr(o\text{-}C_6H_4CH_2CON(H)Bn)\{(S)\text{-BINAP}\}]$ (**1**) mostra o anel aromático aproximadamente perpendicular ao plano de coordenação com geometria quadrática plana ao redor do átomo de paládio. Como estes complexos apresentam rotação restrita da ligação paládio-aril e um ligante quiral, dois diastereoisômeros foram observados por $^{31}P\{^1H\}$ NMR. O comportamento dinâmico do complexo **1** em solução de $CDCl_3$ foi estudado por RMN de $^{31}P\{^1H\}$ (**1**, ^{13}CO-**1** e ^{15}N-**1**) a varias temperaturas. O complexo enriquecido com ^{13}CO foi estudado também por RMN de $^{13}C\{^1H\}$. Três espécies foram detectadas por RMN de $^{31}P\{^1H\}$ e $^{13}C\{^1H\}$ a baixas temperaturas (< 0 °C) e foram atribuídas como sendo os dois diastereoisomeros de **1** e o complexo catiônico $[Pd(o\text{-}C_6H_4CH_2CON(H)Bn)\ \{(S)\text{-BINAP}\}]^+Br^-$. Acima de 40 °C observou-se somente os dois diastereoisômeros e a coalescência dos sinais pode ser observada por RMN de $^{13}C\{^1H\}$ a 80 °C. Não foi observada, na escala de tempo de RMN, nenhuma interconversão do complexo **1** em tol-d_8 entre –35 at 120 °C. Entretanto, a interconversão entre os dois diastereoisômeros foi evidenciada por experimento de transferência de inversão no RMN de $^{31}P\{^1H\}$. Os ciclopaladatos $[Pd(o\text{-}C_6H_4CH_2CONBn)L_2]$ [**11** L_2= DPPF, 68%; **12** L_2 = (S)-BINAP, 88 %] foram obtidos a partir das reações entre os complexos com NaO-*t*-Pn. A análise de RMN de $^{31}P\{^1H\}$ dos complexos **11** e **12** marcados com ^{15}N mostrou a presença da ligação Pd-N. A decomposição térmica do paladaciclo **12** conduziu ao heterociclo esperado e a uma amida como produto de redução.

The complexes resulting from the 1:4 mixture of $[Pd_2(dba)_3]$ and P(*o*-tolyl)$_3$ in benzene react with ortho substituted-arylbromides to generate *in situ* the corresponding bromide dimer $[Pd(Ar)(\mu\text{-}Br)\{P(o\text{-tolyl})_3\}]_2$. Addition of 2 equiv. of (S)-BINAP gave the corresponding $[PdBr(o\text{-}RC_6H_4)\{(S)\text{-BINAP}\}]$ in good yields (57-89%). The crystal structure of $[PdBr(o\text{-}C_6H_4CH_2CON(H)Bn)\{(S)\text{-BINAP}\}]$ (**1**) shows a square planar arrangement around palladium with the aryl ring positioned nearly perpendicular to the square-planar coordination plane. Since these complexes exhibit restricted rotation about the palladium-aryl bond and contain a chiral ligand, they exist as two distinct diastereoisomers discernable by $^{31}P\{^1H\}$ NMR. The dynamic behavior of the complexes **1**, ^{13}CO-**1**, and ^{15}N-**1** in $CDCl_3$ was studied by $^{31}P\{^1H\}$ NMR spectroscopy. ^{13}CO-labeled **1** was also studied by $^{13}C\{^1H\}$ NMR. At temperatures below 0 °C three species were detected on the $^{31}P\{^1H\}$ and $^{13}C\{^1H\}$ NMR time scale. They were assigned as the two diastereoisomers and the cationic complex $[Pd(o\text{-}C_6H_4CH_2CON(H)Bn)\ \{(S)\text{-BINAP}\}]^+Br$. Above 40 °C only the two diastereoisomers were detectable. At higher temperatures rotation increased and at 80 °C a coalescence of the signals was observed by $^{13}C\{^1H\}$ NMR. However, no interconversion was observed for **1** in tol-d_8 in the –35-120 °C range on the NMR time scale. In addition, the existence of the interconversion between the two isomers was directly demonstrated by an inversion transfer ^{31}P NMR experiment. The cyclopalladated complexes $[Pd(o\text{-}C_6H_4CH_2CONBn)L_2]$ [**11** L_2= DPPF, 68% yield; **12** L_2 = (S)-BINAP, 88 yield] were obtained by treatment of the aryl bromide complexes with NaO-*t*-Pn. $^{31}P\{^1H\}$ NMR spectra of the ^{15}N labeled complexes **11** and **12** clearly showed a Pd-N bond. Decomposition of the palladacycle **12** afforded the heterocycle and the amide reduced product.

Keywords: palladium, palladacycles, amidation, heterocycles, restricted rotation

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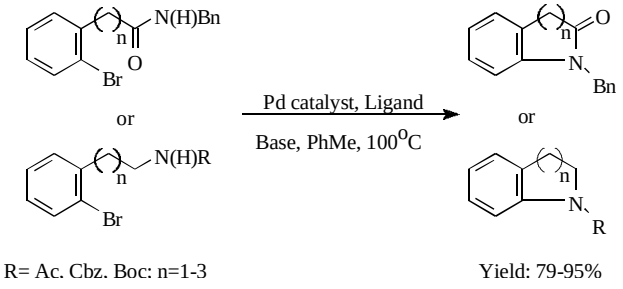
Introduction

The palladium-catalyzed amination developed by Buchwald and Hartwig is a powerful tool for producing nitrogen heterocycles, which are one of the most important classes of pharmacologically active compounds.[1,2] In particular, Buchwald reported that aryl bromides with pendant secondary amide groups could be cyclized to form tertiary amides.[3] P(*o*-tolyl)$_3$ or P(2-furyl)$_3$ were the ligands used in conjunction with [Pd$_2$(dba)$_3$]. This methodology allows for easy access to a wide variety of nitrogen heterocycles. However, these cyclization protocols typically employed high catalyst loadings and often long reaction times were necessary. Furthermore, while this methodology did allow for the formation of five- and six-membered rings, the preparation of seven-membered rings proceeded in low overall yield. However, with the proper choice of palladium catalyst, ligand and base, five-, six-, and seven-membered rings are formed efficiently from secondary amide or secondary carbamates precursors (Scheme 1).[4] While BINAP [2,2'-bis(diphenylphosphino)-1,1'-binaphthyl] and DPEphos [bis(2-diphenylphosphinophenyl)ether] are often suitable for the formation of five- and six-membered ring products MOP [2-(diphenylphosphino)-2'-methoxy-1-1'-binaphthyl] and Xantphos [9,9-dimethyl-4,5-bis(diphenylphosphino)xanthene] are the ligands of choice for the formation of seven-membered rings. On the other hand, Xantphos is also effective for the intermolecular C-N bond-forming reactions between aryl halides and amides.[5]



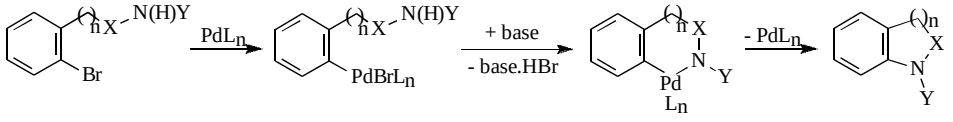
Scheme 1.

In analogy with palladium-catalyzed aminations of aryl halides reactions, an oversimplified catalytic cycle is shown in Scheme 2.[1] Oxidative addition of the aryl bromide to L$_n$Pd(0) complex gives the intermediate Pd(II) complex.[6] Deprotonation gives the palladacycle that can reductively eliminate to produce the desired heterocycle and regenerate the Pd(0) catalyst.[7] In the intramolecular process, the coordination of the amide prior to the deprotonation of the Pd(II) intermediate is facilitated by the linkage of the amine moiety to the aryl group. The difference of activity observed in the formation of the five-, six-, seven- and eight-member rings could be related to the stability of the palladacycle intermediate. Due to the central role of the palladium complex formed from the oxidative addition of aryl bromide to the Pd(0) as well the palladacycle complex in the overall catalytic cycle,[8] we have been interested in the factors which influence both the formation and reactivity of these complexes. On the other hand, BINAP is an important ligand for the amination of aryl bromides.[9] In this paper are report the synthesis and characterization of a series of [PdBr(*o*-substitutedAr){(S)-BINAP}] complexes , the reaction of these complexes with base giving the palladacycle complexes,and their reactivity.

Results and Discussion

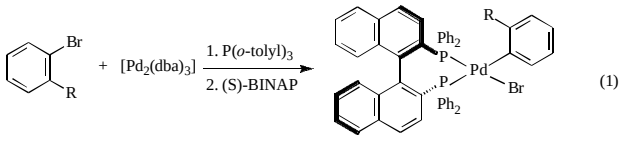
Synthesis of the oxidative addition complexes [PdBr(o-substituted-Ar){(S)-BINAP}]

The complexes [Pd(Ar)Br{(S)-BINAP}] could not be obtained directly from the oxidative addition of aryl bromide to a mixture of [Pd$_2$(dba)$_3$] and (S)-BINAP. In fact, stirring a purple solution of [Pd$_2$(dba)$_3$], (S)-BINAP and aryl bromide at room temperature for 24 h gave an orange solution from which [Pd(BINAP)(dba)] was the only product detected by ^{31}P NMR spectroscopy.[10] The oxidative addition complex could be detected by ^{31}P NMR spectroscopy when the reaction was carried out at 80 °C, but the selectivity was low for synthetic purposes. Buchwald has demonstrated that the palladium complexes [Pd(Ar)Br{(S)-BINAP}] can been obtained in two steps from [Pd$_2$(dba)$_3$].[11] First the palladium tri-o-tolyphosphine dimer [Pd(μ-Br)(*p*-C$_6$H$_4$CN){P(*o*-tolyl)$_3$}]$_2$ was isolated in good yield (75%) from the reaction of [Pd$_2$(dba)$_3$] with *p*-CNC$_6$H$_4$Br and P(o-tolyl)$_3$ in benzene.[12] Second, reaction of the complex [Pd(μ-Br)(*p*-C$_6$H$_4$CN){P(*o*-tolyl)$_3$}]$_2$ with (S)-BINAP in dichloromethane gave the complex [PdBr(*p*-C$_6$H$_4$CN){(S)-BINAP}] in 80% yield. In order to obtain the BINAP-Pd complex in one step, we have carried out some



Scheme 2.

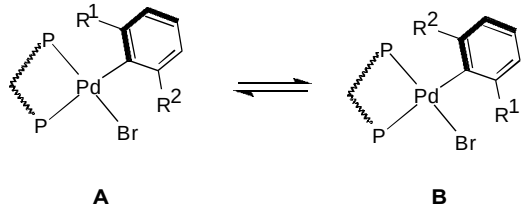
modifications to the protocol. The complexes resulting from a 1:4 mixture of $[Pd_2(dba)_3]$ and P(*o*-tolyl)$_3$ in benzene react with arylbromide to generate *in situ* the corresponding bromide dimer $[Pd(Ar)(\mu\text{-}Br)\{P(o\text{-tolyl})_3\}]_2$. Addition of 2 equivalents of (S)-BINAP gives the corresponding [Pd(Ar)(Br){(S)-BINAP}]. Using this procedure the complex [PdBr(*p*-C_6H_4CN){(S)-BINAP}] was isolated in 80% yield in one step. The ^{31}P NMR {^1H} spectrum displayed two doublets at δ 12.9 and 27.9 ($^3J_{P\text{-}P}$ 38 Hz), which characterized bidentate coordination of the phosphine ligand to the palladium center having two nonequivalent phosphorus containing groups.[11]



(1)

The one-pot procedure was applied for the preparation of oxidative addition complexes containing *o*-substituted primary amide moieties on the aryl group, in good yields (equation 1 and Table 1). The complexes were characterized by standard spectroscopic techniques and elemental analysis and the structure of the complex **1** in the solid state was determined by an X-ray diffraction study . $^{31}P\{^1H\}$ NMR analysis of [PdBr(*o*-$C_6H_4CH_2CON(H)Bn$){(S)-BINAP}] (**1**) in C_6D_6 showed two distinct species, each having two doublets (δ 10.2 and 26.3; δ 11.6 and 24.8 respectively) with $^3J_{P\text{-}P}$ 37 Hz. The $^{13}C\{^1H\}$ NMR spectrum for ^{13}C labeled **1a** in C_6D_6 displayed two signals for ^{13}C=O (δ 171.4 and 171.5) and the ratio of these resonances was the same as observed in ^{31}P NMR. ^{15}N labeled **1b** did not display any additional coupling in the $^{31}P\{^1H\}$ NMR spectrum confirming that none of the species has nitrogen coordinated to the palladium atom.

The presence of two species in solution is not restricted to the complexes having an amido moiety in the ortho position (**1-3**). In fact, two species were also detected in $^{31}P\{^1H\}$ NMR spectra for the complexes with a carbonyl (**4**), hydroxyl (**5**) or even alkyl moiety (**6-8**), and the ratio depends on the R group. These results can be explained by the restricted rotation about the palladium-aryl bond (Scheme 3).[13] X-ray structural analysis of complex **1** showed that the aryl group is close to orthogonality to the coordination plane (see X-ray structure discussion). In the case of *o*-substituted aryl complexes, if the rotation is restricted and the chelating ligand is a C_2 symmetrical chiral ligand such as (S)-BINAP two diastereoisomer or rotamers are possible. However, if the chelating phosphine is symmetrical and achiral only one complex is expected. For comparison, a complex of the achiral ligand DPPF [1,1'-bis(diphenylphosphino)ferrocene] was prepared using the same procedure affording 79% of [PdBr(*o*-$C_6H_4CH_2CONHBn$)(DPPF)] (**9**).[14] This complex was fully characterized by standard spectroscopic techniques and elemental analysis and, as expected, only one species was observed by $^{31}P\{^1H\}$ NMR (δ 7.7 and 28.4; *J* 32 Hz).



P~P = achiral; **A** = **B**
P~P = chiral; $R^1 = R^2$; **A** = **B**
P~P = chiral; $R^1 \neq R^2$; **A** ≠ **B**

Scheme 3.

X-ray structure of [PdBr(o-$C_6H_4CH_2CON(H)Bn$){(S)-BINAP}] (1)

The crystal structure of complex **1** was examined by X-ray diffraction. Selected bond lengths and angles are listed in Table 2. The structure obtained is shown in Figure 1 and reveals a distorted-square planar arrangement about the palladium atom. The C31-Pd-P1 angle is 173.3(2) and the

Table 1. Palladium *o*-substituted aryl l bromide complexes [PdBr(*o*-C_6H_4R){ (S)-BINAP}]

complex	R	Yield (%)	$^{31}P\{^1H\}$ NMR (δ in ppm)
1	$CH_2CON(H)Bn$	76	10.2 and 26.3 (54%) / 11.6 and 24.8 (46%)
1a	$CH_2{}^{13}CON(H)Bn$	79	54 : 46
1b	$CH_2CO^{15}N(H)Bn$	77	54 : 46
2	$CH_2CH_2CON(H)Bn$	74	9.9 and 26.9 (62%) / 11.9 and 25.2 (38%)
3	$CH_2CH_2N(H)Ac$	69	10.5 and 27.4 (25%) / 11.5 and 26.1 (75%)
4	$CH_2CH_2COCH_3$	61	9.7 and 27.0 (59%) / 12.0 and 25.0 (41%)
5	CH_2CH_2OH	79	10.2 and 26.7 (55%) / 11.8 and 24.8 (45%)
6	Me	89	10.0 and 26.5 (63%) / 10.7 and 23.5 (37%)
7	*I*Pr	57	9.5 and 26.6 (13%) / 12.0 and 25.0 (87%)
8	Ph	59	11.4 and 25.8 (1%) / 14.0 and 26.3 (99%)

P2-Pd-Br angle is 170.4(7) rather than the ideal 180°. The sum of the four angles at Pd involving P1, P2, C31, and Br is 360.7°. The bite angle of the BINAP ligand (92.57(8)°) is in the range observed for BINAP-Pd complexes (90.7-95.8°).[15] As observed by others [PdArXL$_2$] (L$_2$ = bidentate ligand, X= halogen) complexes and expected by the trans influence, the Pd-P bond length trans to the aryl is longer than Pd-P bond length trans to the halogen, 2.396(2) and 2.269(2) Å, respectively.[16-18] The aryl group is not perfectly orthogonal with the coordination plane [torsion angles (C32(ortho)-C31(ipso))- (Pd-P2) = 103.9°, (C36(ortho)-C31(ipso))- (Pd-P2) = 81.4°, (C36(ortho)-C31(ipso))- (Pd-Br) = 89.1°, (C32(ortho)-C31(ipso))- (Pd-Br) = 85.6°). Another similarity with other [PdArXL$_2$] (L$_2$ = bidentate ligand, X= Cl[18], Br[17], I[16]) complexes, is that the X-Pd-aryl angle is shorter than X-Pd-P [Br-Pd-C31 = 85.7(2)° and Br-Pd-P1 = 89.45(6)]. Since the distance N---Br is 3,573 Å (Br----H-N = 169°), no interaction or a very weak intramolecular hydrogen bond is involved.

Table 2. Selected bond lengths (A°) and angles (deg) for [PdBr(*o*-C$_6$H$_4$CH$_2$CON(H)Bn){(S)-BINAP}] (**1**) with estimated standard deviations in parentheses

		Bond Distances	
Pd-C31	2.030(9)	P2-C211	1.820(9)
Pd-P2	2.269(2)	P2-C21	1.846(9)
Pd-P1	2.396(2)	O-C38	1.189(10)
Pd-Br	2.4830(11)	N-C38	1.346(11)
P1-C117	1.814(9)	N-C39	1.454(11)
P1-C111	1.822(9)	C11-C12	1.363(11)
P1-C11	1.843(9)	C12-C22	1.503(11)
P2-C217	1.808(9)	C21-C22	1.380(11)
		Bond Angles	
C31-Pd-P2	93.0(2)	C211-P2-Pd	114.9(3)
C31-Pd-P1	173.3(2)	C21-P2-Pd	103.3(3)
P2-Pd-P1	92.57(8)	C38-N-C39	121.0(8)
C31-Pd-Br	85.7(2)	C13-C12-C22	116.8(7)
P2-Pd-Br	170.40(7)	C21-C22-C12	121.7(8)
P1-Pd-Br	89.45(6)	C11-C12-C22	120.8(8)
C117-P1-Pd	113.8(4)	O-C38-N	124.1(9)
C111-P1-Pd	113.2(3)	O-C38-C37	123.3(9)
C11-P1-Pd	115.7(3)	N-C38-C37	112.6(8)
C217-P2-Pd	124.6(3)	N-C39-C310	113.9(8)

*NMR observations on [PdBr(o-C$_6$H$_4$CH$_2$CON(H)Bn){(S)-BINAP}] (**1**)*

The NMR spectra of **1** are very dependent on the solvent used. As already mentioned, ^{31}P{^{1}H} NMR analysis of **1** shows two distinct species, each one having two doublets with $^3J_{P\text{-}P}$ 37 Hz C$_6$D$_6$ (δ 10.2 and 26.3; δ 11.6 and 24.8). However, ^{31}P{^{1}H} NMR spectrum of **1** in DMF-d$_7$ displayed two very broad signals centered at δ 10.0 and 28.0. A more complicated pattern was observed in CDCl$_3$. Figure 2 shows the ^{31}P{^{1}H} NMR spectra for the ^{13}C labeled **1a** in the –35-80 °C range. It is important to note that variable temperature ^{31}P{^{1}H} NMR analysis of **1**, and ^{13}C labeled **1a** in CDCl$_3$ give rise to identical spectra.

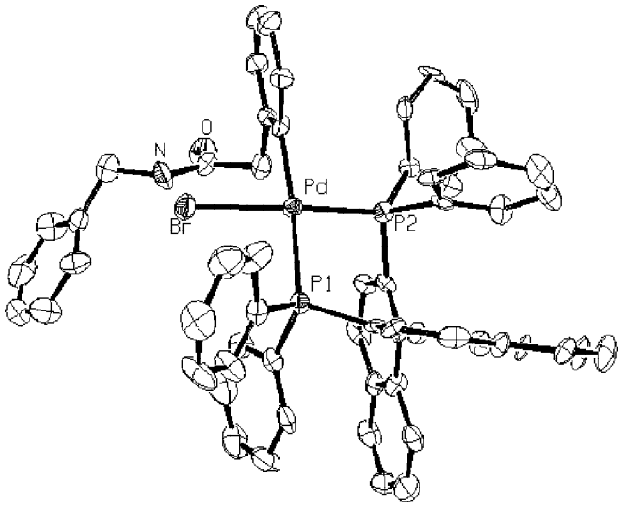


Figure 1. ORTEP drawing of the molecular structure of [PdBr(o-C$_6$H$_4$CH$_2$CON(H)Bn){(S)-BINAP}] (**1**).

The ^{31}P{^{1}H} NMR spectrum at room temperature displayed one pair of doublets (δ 10.8 and 28.5, *J* 37.0 Hz) instead of the two observed in C$_6$D$_6$ or tol-d$_8$. Besides this pair of doublets, three broad signals centered at δ 12.1, 25.4 and 38.7 were also observed (Figure 2). When the temperature was lowered to 0 °C the broad signals centered at δ 25.4 and 38.7 became partially resolved into doublets, while the broad signal at δ 13 was split into two partially resolved doublets. Three sharp pairs of doublets were observed at –25 °C evidencing the existence of three species containing the bidentate BINAP ligand coordinated to the palladium [A: δ 10.8 and 28.5 (*J* 37.0 Hz); B: δ 12.2 and 28.5 (*J* 38.0 Hz); C: δ 13.9 and 38.9 (*J* 43.0 Hz)]; there is no change in the shape and position of the pair of doublets observed at room temperature (species A). However, the relative ratio of the three species changes with temperature and the species C characterized by the doublets at δ 13.8 and 38.8 is favored at low temperatures. The fluxional behavior of **1a** in CDCl$_3$ was also investigated by ^{13}C{^{1}H} NMR analysis of the ^{13}C-labeled carbonyl group (Figure 3). One relative sharp signal at δ 172.8 and one broad signal at δ 173.5 were observed at room temperature. At 0 °C the broad signal decreased in intensity and a third broad signal appeared at δ 174.6. By lowering the temperature these signals became sharp and, in agreement with ^{31}P NMR, the presence of three species was also evidenced. When the temperature was lowered to –35 °C the relative intensity of the signal at δ 174.6

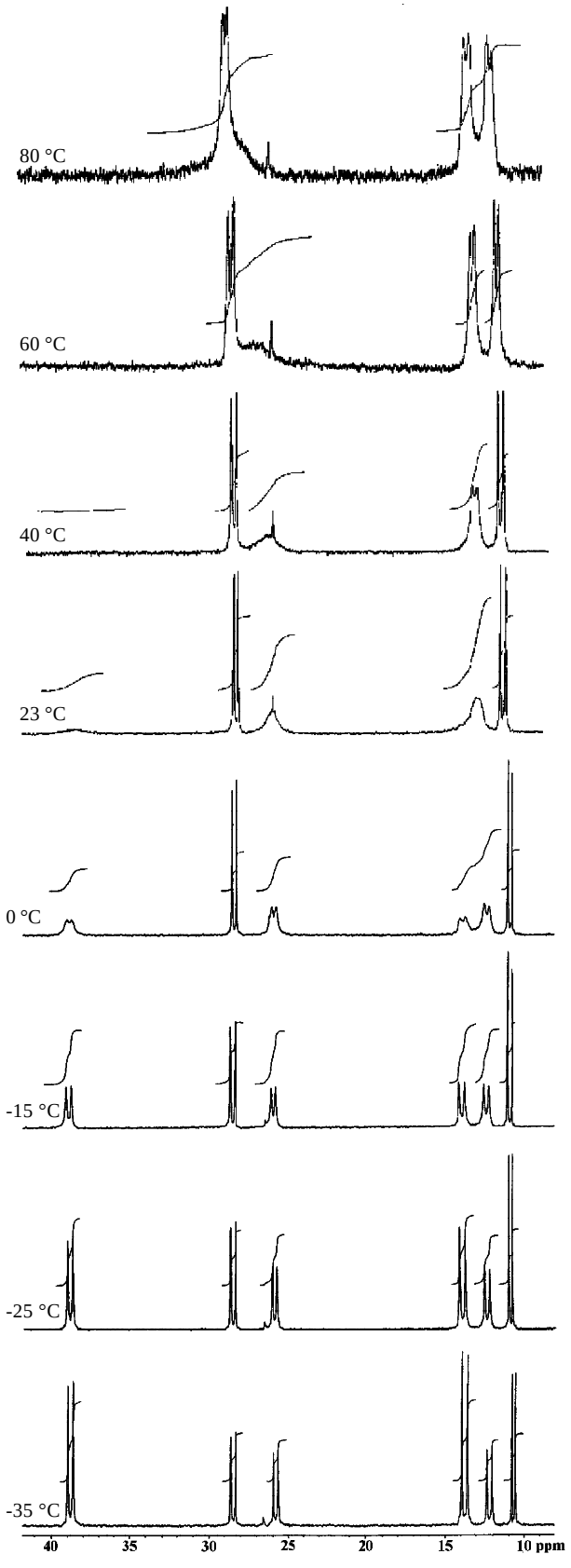


Figure 2. $^{31}P\{^{1}H\}$ NMR spectra of **1a** in $CDCl_3$ solution in the -35-80 °C temperature range.

increased showing that this carbonyl resonance was related to species C with $^{31}P\{^{1}H\}$ NMR resonances at δ 13.8 and 38.8. $^{31}P\{^{1}H\}$ and $^{13}C\{^{1}H\}$ NMR spectra above room temperature indicated two species between 40 and 80 °C, with a coalescence temperature at 80 °C in $^{13}C\{^{1}H\}$ NMR. From this coalescence temperature, an approximate rate of 10^2 s^{-1} and a free energy of activation ($\Delta G^{\neq}$) of 17 Kcal/mol were calculated. These results are similar to those obtained for other arylpalladium complexes with restricted rotation, but the coalescence temperature is higher (80° versus room temperature).[19]

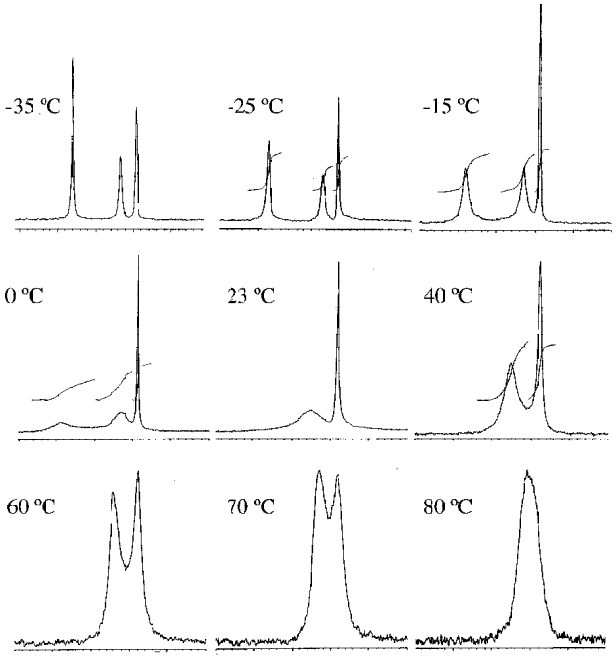
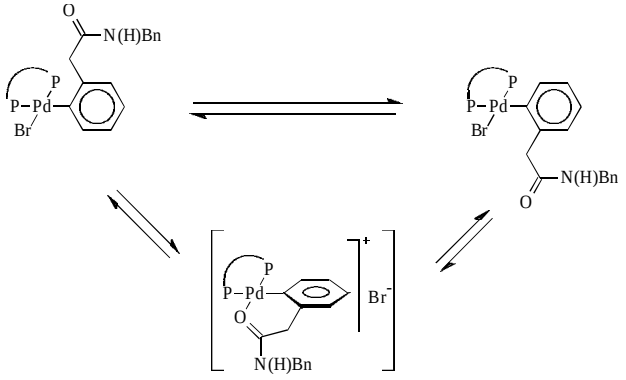


Figure 3. $^{13}C\{^{1}H\}$ NMR spectra of **1a** in $CDCl_3$ solution in the -35-80 °C temperature range.

By comparison with the chemical shift of complexes **2** to **8** and also with **1** in C_6D_6, the species A and B, characterized by the pair of doublets at δ 10.8/28.5 and 12.2/25.9 in $CDCl_3$, can be assigned as two diasteroisomers that can interconvert by rotation around the Pd-C_{ipso} bond. In the case of the complex [PdBr{*o*-$C_6H_4(CH_2CH_2OH)$}(tmeda)], van Koten proposed that the rapid rotation of the aryl group around the Pd-C_{ipso} bond was induced by an intramolecular substitution of the bromide ligand by hydroxyl group leading to a cationic intermediate.[19] In order to verify this possibility, complex **1** was partially dissolved in acetone-d_6 and reacted with excess of AgOTf. $^{31}P\{^{1}H\}$ NMR before reaction displayed two pairs of relatively broad doublets but the chemical shifts (δ 11.1/28.6 and 11.9/27) are similar to those obtained in $CDCl_3$. After stirring the mixture and filtration, the yellow solution displayed only one sharp pair of

doublets at δ 14.7 and 39.0 (J 44 Hz), very close to the chemical shift for the third species observed at low temperatures. The reaction was also carried out with the ^{13}C-labeled complex **1a** giving a chemical shift of 175.8 for the carbonyl group of the cationic complex (compared with δ 174.6 for species C in $CDCl_3$). It is interesting to note that a very small coupling (2 Hz) was observed for this resonance. $^{31}P\{^1H\}$ NMR analysis of the ^{15}N-labeled complex **1b** showed a doublet of doublets only for the resonance at δ 39.0 ($J_{P\text{-}P}$ 44 Hz and $J_{P\text{-}N}$ 2 Hz). The chemical shift observed and the presence of very small couplings for the complexes **1a** and **1b** are in agreement with a cationic complex with the amido group coordinated to palladium by the oxygen atom. Scheme 4 summarizes the fluxional behavior of the complex **1** in $CDCl_3$. At low temperatures (below 0 °C) the two diastereoisomers and the cationic complex are detectable on the NMR time scale. Above 40 °C only the two diastereoisomers are detectable. When the temperature is raised the rotation became faster and at 80 °C a coalescence of the signals was observed. The interconversion of the diastereoisomers can occur via the cationic complex and/or by simple rotation by 180° of the aryl ring around the Pd-C_{ipso} bond.



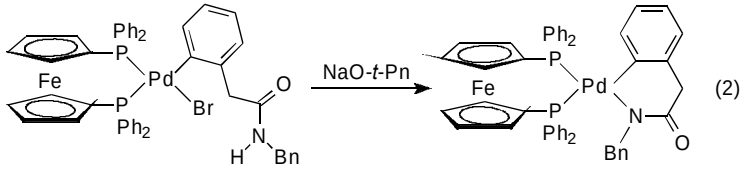
Scheme 4.

In opposition, no fluxional behavior was observed in tol-d_8, and complex **1** was characterized by two sharp pairs of doublets in the –35-120 °C range. Thus, no interconversion between the two diastereoisomeric forms was observed on the NMR time scale. However, the existence of the interconversion between the two isomers was directly demonstrated by an inversion transfer ^{31}P NMR experiment. Selective inversion of the doublet at δ 11.4 results, after an appropriate evolution time, in a significant change in the intensity of the doublet at δ 12.9 (see electronic supplementary information). A maximum decrease in relative intensity for the doublet at δ 12.9 was observed using a evolution time of 0.5 seconds, while the doublets at δ 26.0 and 27.4 remained unchanged for all the evolution time evaluated. In the same way, selective inversion of the doublet at δ 27.4 results in a significant change only for the doublet at δ 26.0, and a maximum decrease in intensity was also observed for a evolution time of 0.5 seconds. These results show the existence of an exchange process between the phosphorus atoms characterized by the resonances at δ 11.4 and 12.9, and between the phosphorus atoms characterized by the resonances at δ 26.0 and 27.4. The doublets at δ 11.4 and 12.9 were assigned to the phosphorus *cis* to the bromine for each isomer, and the doublets at δ 26.0 and 27.4 as the phosphorus *cis* to the aryl moiety for each isomer (vide infra). The exchanges observed by the inversion transfer experiment can be explained by an interconversion between the two isomers caused by simple 180° rotation of the aryl ring around the Pd-C_{ipso} bond or via a cationic complex as observed in $CDCl_3$. However, the interconversion in tol-d_8 is slower and can only be observed using a inversion transfer experiment.

Synthesis and characterization of the cyclopalladated complexes [Pd(o-$C_6H_4CH_2CONBn)L_2$]

In order to obtain the palladacycle, the aryl bromide complexes were reacted with a base in benzene. Effective bases for palladium-catalyzed cyclization of secondary amides and carbamates, such as Cs_2CO_3 and K_2CO_3, were completely inactive at room temperature, and the starting complex **1** was recovered unchanged at the end of the reaction. Only decomposition to metallic palladium was observed by increasing the temperature (up to 100 °C). However, the palladacycle [Pd(*o*-$C_6H_4CH_2$CONBn)(DPPF)] (**10**) was isolated free from NaBr and excess alkoxide in 68% yield by treatment of the aryl bromide complex [PdBr(*o*-$C_6H_4CH_2$CONHBn)(DPPF)] (**9**) with NaO-*t*-Pn in benzene at room temperature (equation 2).

Palladacycle **10** was characterized by spectroscopy and elemental analysis. A comparison with selected data from the starting complex is shown in Table 5. For example, its IR spectrum shows the disappearance of the $\nu_{N\text{-}H}$ absorption and a carbonyl absorption at 1594 cm^{-1} (compared with 1679 cm^{-1} for the starting complex) characteristic of a M-NCOR complex.[20] $^{31}P\{^1H\}$ NMR spectrum displayed two doublets at δ 10.0 and 25.4 ($^2J_{P\text{-}P}$ 35 Hz) for the palladacycle and two doublets at δ 7.7 and 28.4 ($^2J_{P\text{-}P}$ 32 Hz) for the starting aryl bromide palladium complex **9**. $^{31}P\{^1H\}$ NMR analysis of the reaction of the ^{15}N-labeled complex **10** with NaO-*t*-Pn established nitrogen coordination to palladium. In fact, the resulting complex displayed a doublet of doublets for signals at δ 10.0 and 25.4 with a $^2J_{P\text{-}N}$ of 3.7 and 47.6 Hz, respectively. Trans-$^2J_{P\text{-}N}$ values are



(2)

9 **10** : 68%

Table 5. Spectroscopic data for aryl bromide complexes **1** and **9** and their respective palladacycles **11** and **10**

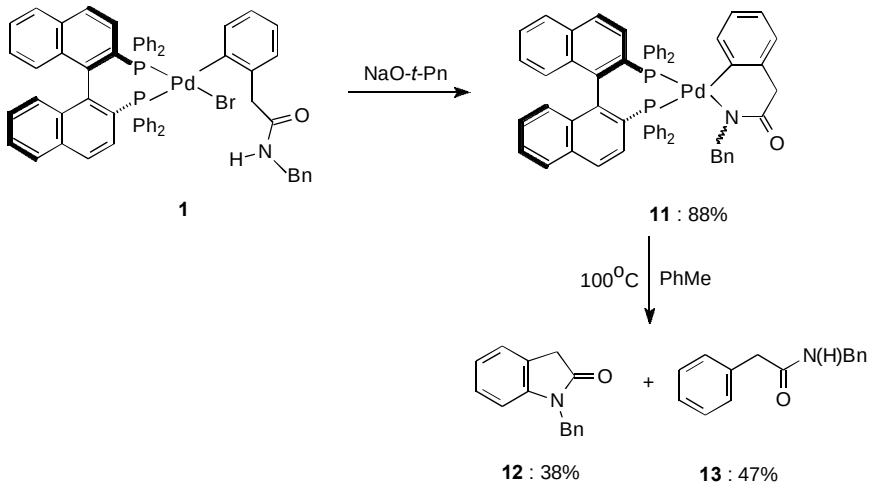
	9	**10**	**1**	**11**
$^{31}P\{^{1}H\}$ NMR: δ (ppm)	7.7 and 28.4	10.0 and 25.4	10.2 and 26.3 (54%) 11.6 and 24.8 (46%)	12.3 and 30.3 (41%) 13.3 and 28.9 (59%)
$^{3}J_{P\text{-}P}$ (Hz)	32.4 and 31.7	35.4 and 34.8	37.2 and 37.8 38.4 and 37.2	8.5 and 39.1 334.8 and 36.0
$^{3}J_{P\text{-}N}$ (Hz)	-	3.7 and 47.6	-	44.5 for δ 30.3 46.0 for δ 28.9
$^{13}C\{^{1}H\}$ NMR: $\delta_{C=O}$ (ppm)	172.0	174.4	171.4 and 171.5	174.7 and 175.8
IR $\nu_{max(C=O)}$ / cm^{-1}	1679	1594	1669	1588
IR $\nu_{max(N\text{-}H)}$ / cm^{-1}	3315	-	3307	-

higher than those for cis couplings.[21,22] For instance, it has been reported that cis $^{2}J_{P\text{-}N}$ couplings for Pd(II), Pt(II) and Au(III) complexes are very small compared with trans couplings (<2 Hz and ~50 Hz, respectively).[21] In complex **10**, the low frequency resonance (δ 10.0) must therefore be assigned to the phosphorus *cis* to the nitrogen, and the high frequency resonance (δ 25.4) corresponds to the phosphorus *trans* to nitrogen. By analogy, the resonances at δ 7.7 and 28.4 in complex **9** can be assigned to the phosphorus *cis* and *trans* to the bromine, respectively.

In the same way, the palladacycle [Pd(*o*-$C_6H_4CH_2CONBn$){(S)-BINAP}] (**11**) was isolated in 88% yield by treatment of the aryl bromide complex [PdBr(*o*-$C_6H_4CH_2CONHBn$){(S)-BINAP}] (**1**) with NaO-*t*-Pn in benzene at room temperature (Scheme 5). Palladacycle **11** was characterized by spectroscopy and elemental analysis, and a comparison with selected data from the starting complex is shown in Table 5. Similar results with those observed for the DPPF-cyclopalladated complex **10** were obtained for the (S)-BINAP-cyclopalladated complex **11**. IR analysis showed carbonyl absorption at 1558 cm^{-1} (compare with 1669 cm^{-1} for the starting complex) and the disappearance of the $\nu_{N\text{-}H}$ absorption. For the starting complex **1**, two isomers were observed by $^{31}P\{^{1}H\}$ NMR analysis for the deprotonated complex **11** (Scheme 5). For each isomer the phosphorus at low field is characterized as a doublet of doublets ($^{3}J_{P\text{-}N}$ 46 Hz and $^{3}J_{P\text{-}P}$ 36 Hz) evidencing the presence of a palladium-nitrogen bond and that these resonances at low field must be assigned to a phosphorus *trans* to the nitrogen and *cis* to the aryl moiety. In the palladacycle **11**, pyramidal inversion of the nitrogen atom must be very slow or has ceased completely and the conjunction of a chiral nitrogen and a chiral BINAP ligand generates two diastereoisomers [Pd{(S)-*o*-$C_6H_4CH_2CONBn$}{(S)-BINAP}] and [Pd{(R)-*o*-$C_6H_4CH_2CONBn$}{(S)-BINAP}]. When complex **11** is heated at 100 °C in toluene decomposition to metallic palladium with formation of the heterocycle **12** and the amide **13** was observed. It is interesting to note that in catalytic conditions the amide **13** is observed as by-product but in very low proportions (<2%) under optimized conditions.

Conclusions

In conclusion, *o*-substituted aryl palladium complexes are obtained in one step in good yields (57-89%). Since these complexes exhibit restricted rotation about the palladium-aryl bond and contain a chiral ligand, they exist as two distinct diastereoisomers discernable at rt by $^{31}P\{^{1}H\}$ NMR. Only the complex [PdBr{*o*-$C_6H_4CH_2CONHBn$}{(S)-BINAP}] **1** in $CDCl_3$ is dynamic on the NMR time scale at room temperature. At low temperatures (below O°C) three species were detectable on the ^{31}P and ^{13}C NMR time scale. They are assigned as the two diastereoisomers and the cationic complex [Pd(*o*-$C_6H_4CH_2CON(H)Bn$}{(S)-BINAP}]$^{+}Br^{-}$. Above 40 °C only the two diastereoisomers are detectable. When the temperature is raised the rotation



Scheme 5.

became faster and at 80 °C a coalescence of the signals was observed in $^{13}C\{^1H\}$ NMR. The interconversion of the diastereoisomers can occur via the cationic complex and/or by simple rotation by 180° of the aryl ring around the Pd-C_{ipso} bond. In opposition, no interconversion was observed for **1** in tol-d_8 in the –35 to 120 °C temperature range on the NMR timescale. However, the existence of the interconversion between the two isomers was directly demonstrated by an inversion transfer ^{31}P NMR experiment**.** Such observations of large rotational barriers about the palladium-aryl bond in *o*-substituted aryl palladium complexes, associated with the dependence on the group R and the diastereoselectivities observed in BINAP complexes, could be useful for understanding the asymmetric cross-coupling reaction using ortho-substituted aryl halides.

The palladacycle complexes were obtained in good yields by treatment of the aryl bromide complexes with NaO-*t*-Pn in benzene at room temperature. The heterocycle formed from the reductive elimination of complex [Pd(*o*-$C_6H_4CH_2CONBn$){(S)-BINAP}] was obtained with metallic palladium when the complex was heated at 100 °C in toluene. The species described in this work corresponds to the postulated intermediate for the palladium-catalyzed intramolecular amidation reaction and a correlation with a mechanistic study under catalytic conditions should follow.

Experimental

General methods

$[Pd_2(dba)_3]$, arylbromides, and phosphines were manipulated in air. All other manipulations were performed under an atmosphere of nitrogen or argon in a glovebox or by standard Schlenk techniques. NMR spectra were recorded on a Varian Unity-300, Varian Mercury-300 or Varian 500 at 23 °C unless otherwise noted. ^1H and ^{13}C (75.6 MHz) spectra were referenced relative to the residual solvent peak. ^{31}P NMR (121.5 MHz) spectra were referenced relative to external 85% H_3PO_4. IR spectra were recorded on a ASI ReactIR 1000 spectrometer. Elemental analyses were performed by E&R Microanalytical Laboratories (Parsippany, NJ).

Diethyl ether was distilled from solutions of sodium/benzophenone under argon. $CDCl_3$, C_6D_6, and PhMe-d_8 (Cambridge Isotopes) were dried over 4A° molecular sieves and degassed by three freeze/thaw cycles before use. $[Pd_2(dba)_3]$, P(*o*-tolyl)$_3$, DPPF (Strem), (S)-BINAP (Pfizer), anhydrous benzene, anhydrous hexane, anhydrous pentane, anhydrous dichloromethane, *o*-bromobenzyl-bromide, thionyl chloride, benzylamine, sodium *t*-butoxide, *o*-bromophenethyl alcohol, 2-bromotoluene, 2-bromo-*m*-xylene (Aldrich), 2-bromobiphenyl, 2-bromo-isopropylbenzene (Lancaster), $K^{13}CN$ (Cambridge Isotopes), benzylamine-^{15}N were used as received. *N*-Benzyl-2-*o*-bromophenylethylamide,[3] *N*-benzyl-3-(*o*-bromophenyl)propionylamide,[3] *N*-acetylyl-2-*o*-bromo-phenylethylamine,[3] and 4-(2-Bromophenyl)-2-butanone[23] were synthesized as described in the literature.

Synthesis of ^{13}C- and ^{15}N- labeled N-Benzyl-2-o-bromophenylethylamide

^{13}CN-o-bromophenylacetonitrile. The procedure described for *o*-bromophenylacetonitrile was adapted using $K^{13}CN$.[24]

o-Bromophenylacetonitrile. o-Bromobenzyl bromide (3.76 g, 15.1 mmol) was added to a solution of $K^{13}CN$ (1 g, 15.1 mmol) in 15 mL of ethanol and 10 mL of water. The mixture was refluxed for 1 h, and 100 mL of ice water were added. The mixture was extracted with ether (2 x 100 mL).

The organic extracts were combined, washed with aqueous saturated $NaHCO_3$ (3 x 100 mL), water (3 x 100 mL), brine (2 x 50 mL), dried over anhydrous $MgSO_4$, filtered and concentrated giving a colorless oil (2.64 g, 90%). ^{1}H NMR ($CDCl_3$, 300 MHz) δ 3.85 (d, 2H, *J* 10.4 Hz), 7.23 (t, 1H, *J* 7.6 Hz), 7.37 (t, 1H, *J* 7.5 Hz), 7.53 (d, 1H, *J* 7.7 Hz), 7.61 (d, 1H, *J* 8.0). ^{13}C{^{1}H} NMR ($CDCl_3$, 75.4 MHz) δ 25.0 (d, *J* 58.9 Hz), 117.1, 123.8 (d, *J* 4.5 Hz), 128.3, 129.9 (d, *J* 2.6 Hz) 130.1, 133.3. IR (neat) ν_{max}/cm^{-1}: 3065, 2934, 2196 ($\nu^{13}_{C\equiv N}$), 1594, 1571, 1471, 1440, 1413, 1027, 749, 660. GC/MS (*m/z*) 117, 196, 198, 89, 116, 63, 115, 50.

^{13}CO-o-Bromophenylacetic acid. The procedure described for *o*-bromophenylacetonitrile was employed using ^{13}CN-*o*-bromophenylacetonitrile. A mixture of ^{13}CN -*o*-bromophenylacetonitrile (2.44 g, 12.4 mmol), sulfuric acid (26 mL)and water (35 mL) was refluxed for 4 h. The reaction mixture was poured over ice and, after cooling to room temperature, extracted with ether (3 x 70 mL). The organic extracts were combined and evaporated giving a yellow solid. The crude product was dissolved with aqueous 15% KOH (100 mL), and extracted with ether (2 x 100 mL). The aqueous layer was acidified with aqueous 10% hydrochloric acid giving a white precipitate. After addition of ether (100 mL) the layers were separated and the aqueous layer was washed with ether (100 mL). The organic layers were combined, washed with water (2 x 100 mL), brine (100 mL), dried over anhydrous magnesium sulfate, filtered and concentrated under vacuum to give a white solid (1.69 g, 63%). mp 107-109 °C. ^{1}H NMR ($CDCl_3$, 300 MHz) δ 3.84 (d, 2H, *J* 8.0 Hz), 7.13-7.19 (m, 1H), 7.25-7.30 (m, 2H), 7.57 (d, 1H, *J* 8.0 Hz). ^{13}C{^{1}H} NMR ($CDCl_3$, 75.4 MHz) δ 41.6, 125.3, 127.8, 129.3, 131.7, 133.1, 133.7, 177.1. IR (neat solid) ν_{max}/cm^{-1}: 2926, 1668 ($\nu^{13}_{C=O}$), 1444, 1401, 1343, 1289, 1231, 1197, 1027, 934, 760, 726, 675. Anal Calcd for $C_7{}^{13}CH_7O_2Br$: C, 44.94; H, 3.27%. Found: C, 44.76; H, 3.25%.

General procedure for preparation of N-benzylamides. To solid carboxylic acid (4-10 mmol) in a round bottom flask was added thionyl chloride (8 mL). The solution was stirred at room temperature for 4 h. Excess thionyl chloride was removed *in vacuo* and dichloromethane (5 mL) was added. This solution was slowly added to a solution of benzylamine (2.5 eq.) in dichloromethane (5 mL) at 0 °C; and a white solid precipitated. The reaction mixture was stirred at 0 °C for 30 min, then warned at room temperature and stirred for 1h. The reaction mixture was then diluted with dichloromethane (150 mL), washed with saturated aqueous sodium bicarbonate (50 mL), and washed with brine (2 x 50 mL). The organic layer was dried over anhydrous magnesium sulfate, filtered, and concentrated. The crude product was then purified further by flash chromatography on silica gel.

^{13}CO-N-Benzyl-2-o-bromophenylethylamide. ^{13}CO-*o*-Bromophenylacetic acid was used, and the general procedure gave 1.96 g (87%) of a white solid; mp 133-135 °C. ^{1}H NMR ($CDCl_3$, 500 MHz) δ 3.79 (d, 2H, *J* 7.3 Hz), 4.45 (dd, 2H, *J* 5.5 and 3.0 Hz), 5.73 (br, 1H), 7.16-7.39 (m, 8H), 7.60 (d, 1H, *J* 7.9 Hz). ^{13}C{^{1}H} NMR ($CDCl_3$, 75.4 MHz) δ 43.8, 44.5, 125.1, 127.6, 127.7, 128.3, 128.8, 129.4, 132.0, 133.3, 134.9, 138.2, 169.6.. IR (neat solid) ν_{max}/cm^{-1}: 3273 (ν_{N-H}), 3053, 3030, 2922, 2872, 1606 ($\nu^{13}_{C=O}$), 1536, 1413, 1235, 1027, 733, 691. Anal Calcd for $C^{13}C_{14}H_{14}NOBr$: C, 59.36; H, 4.62%. Found: C, 59.31; H, 4.53%.

^{15}N-Benzyl-2-o-bromophenylethylamide. ^{15}N-benzyl amine was used, and the general procedure gave 0.860 g (84%) of a white solid. mp 131-132 °C. ^{1}H NMR ($CDCl_3$, 500 MHz) δ 3.79 (s, 2H), 4.45 (d, 2H, *J* 5.5 Hz), 5.72 (dt, 1H, *J* 90.6 and 5.8 Hz), 7.15-7.39 (m, 8H), 7.60 (d, 1H, *J* 7.9 Hz). ^{13}C{^{1}H} NMR ($CDCl_3$, 75.4 MHz) δ 43.8 (d, *J* 10.5 Hz), 44.2 (d, *J* 8.4 Hz), 125.1, 127.6, 127.7, 128.2, 128.7, 129.3, 131.9, 133.3, 134.9, 138.2, 169.6 (d, *J* 15 Hz). IR (neat solid) ν_{max}/cm^{-1}: 3266 (ν^{15}_{N-H}), 3030, 2961, 2922, 1644 ($\nu_{C=O}$), 1529, 1455, 1413, 1366, 1339, 1239, 1027, 733, 695. Anal Calcd for $C_{15}H_{14}{}^{15}NOBr$: C, 59.04; H, 4.62%. Found: C, 59.10; H, 4.69%.

General procedure for preparation of [Pd(Ar)(Br){(S)-BINAP}]. A purple solution of [$Pd_2(dba)_3$] (382 mg, 0.418 mmol), P(*o*-tolyl)$_3$ (510 mg, 1.68 mmol) and aryl bromide (1.02 mmol) in benzene (30 mL) was stirred at room temperature for 16 h. (S)-BINAP (520 mg, 0.835 mmol) and benzene (5 mL) were added and the solution was stirred at room temperature for 6 h. The solution was filtered through Celite, and benzene was evaporated under vacuum. The oily residue was dissolved in ether (25 mL) and stirred at room temperature for 16 h. The resulting precipitate was filtered, washed with ether and dried under vacuum.

*[PdBr[o-$C_6H_4CH_2$CON(H)Bn]{(S)-BINAP}] (**1**)*. The general procedure gave 662 mg (76%) of a pale yellow solid that contained traces of ether by ^{1}H NMR analysis (< 5%). ^{1}H NMR (C_6D_6, 300 MHz) (major + minor isomers) δ 3.89 (d, *J* 13.9 Hz), 4.20-4.65 (m), 4.93 (d, *J* 13.9 Hz), 5,15 (d, *J* 14.1 Hz), 6.14-8.21 (m). ^{31}P{^{1}H} NMR (C6D6, 121.5 MHz) major isomer (54%): δ 10.2 (d, *J* 37.2 Hz), 26.3 (d, *J* 37.8 Hz); minor isomer (46%): δ 11.6 (d, *J* 38.4 Hz), 24.8 (d, *J* 37.2 Hz). IR (neat solid) ν_{max}/cm^{-1}: 3301 (ν_{N-H}), 3051, 1669 ($\nu_{C=O}$), 1534, 1497, 1480, 1437, 1308, 1148, 1094, 1021,

872, 816, 739, 691. Anal Calcd for $C_{59}H_{46}NOBrPdP_2$: C, 68.58; H, 4.49%. Found: C, 68.36; H, 4.18%.

[*PdBr(o-$C_6H_4CH_2{}^{13}CON(H)Bn$){(S)-BINAP}] (**1a**)*. The general procedure gave 682 mg (79%) of a pale yellow solid that contained traces of ether by ^{1}H NMR analysis (< 5%). ^{1}H NMR (C_6D_6, 300 MHz) (major + minor isomers) δ 3.89 (dd, *J* 13.5 and 8.3 Hz), 4.19-4.63 (m), 4.93 (dd, *J* 13.5 and 6.4 Hz), 5,15 (dd, *J* 14.2 and 6.4 Hz), 6.13-8.21 (m). ^{31}P{^{1}H} NMR (C_6D_6, 121.5 MHz) major isomer (54%): δ 10.2 (d, *J* 37.2 Hz), 26.3 (d, *J* 37.8 Hz); minor isomer (46%): δ 11.6 (d, *J* 38.5 Hz), 24.8 (d, *J* 38.4 Hz). IR (neat solid) ν_{max}/cm^{-1}: 3305 (ν_{N-H}), 3053, 1630 ($\nu^{13}{}_{C=O}$), 1571, 1526, 1480, 1437, 1308, 1254, 1148, 1094, 1025, 872, 816, 739, 691. Anal Calcd for $C_{58}{}^{13}CH_{46}NOBrPdP_2$: C, 68.76; H, 4.49%. Found: C, 68.64; H, 4.18%.

[*PdBr(o-$C_6H_4CH_2CO^{15}N(H)Bn$){(S)-BINAP}] (**1b**)*. The general procedure gave 666 mg (77%) of a pale yellow solid that contained traces of ether (< 5%) and P(o-tolyl)$_3$ (<1%) by ^{1}H and ^{31} P NMR analysis. ^{1}H NMR (C_6D_6, 300 MHz) (major + minor isomers) δ 3.89 (d, *J* 12.8 Hz), 4.25-4.66 (m), 4.93 (d, *J* 13.6 Hz), 5,15 (d, *J* 14.2 Hz), 6.20-8.21 (m). ^{31}P{^{1}H} NMR (C_6D_6, 121.5 MHz) major isomer (54%): δ 10.2 (d, *J* 37.2 Hz), 26.3 (d, *J* 37.8 Hz); minor isomer (46%): δ 11.6 (d, *J* 38.5 Hz), 24.8 (d, *J* 38.5 Hz). IR (neat solid) ν_{max}/cm^{-1}: 3290 ($\nu^{15}{}_{N-H}$), 3053, 1669 ($\nu_{C=O}$), 1571, 1555, 1520, 1497, 1480, 1437, 1308, 1272, 1258, 1144, 1094, 1023, 872, 816, 741, 693. Anal Calcd for $C_{59}H_{46}{}^{15}NOBrPdP_2$: C, 68.66; H, 4.49%. Found: C, 68.79; H, 4.18%.

[*PdBr(o-$C_6H_4CH_2CH_2CON(H)Bn$){(S)-BINAP}] (**2**)*. The general procedure gave 645 mg (74%) of a pale yellow solid that contained traces of ether by ^{1}H NMR analysis (< 5%). ^{1}H NMR ($CDCl_3$, 300 MHz) major + minor isomers: δ 2.77-2.93 (m), 3.23-3.38 (m), 3.64-3.70 (m), 4.15-4.38 (m), 6.47 (d, *J* 8.5 Hz), 6.55-8.13 (m). ^{31}P{^{1}H} NMR ($CDCl_3$, 121.5 MHz) major isomer (62%): δ 9.9 (d, *J* 37.8 Hz), 26.9 (d, *J* 38.4 Hz); minor isomer (38%): δ 11.9 (d, *J* 39.1 Hz), 25.2 (d, *J* 39.1 Hz). IR (neat solid) ν_{max}/cm^{-1}: 3452 (ν_{N-H}), 3053, 1681 ($\nu_{C=O}$), 1573, 1555, 1505, 1436, 1191, 1092, 1025, 870, 818, 745, 697. Anal Calcd for $C_{60}H_{48}NOBrPdP_2$: C, 68.75; H, 4.45%. Found: C, 68.81; H, 4.62%.

[*PdBr(o-$C_6H_4CH_2CH_2N(H)COCH_3$){(S)-BINAP}] (**3**)*. The general procedure gave 563 mg (69%) of a pale yellow solid that contained traces of ether by ^{1}H NMR analysis (< 5%). ^{1}H NMR ($CDCl_3$, 300 MHz) major + minor isomers: δ 1.67 (s, CH_3, minor isomer), 1.82 (s, CH_3, major isomer), 2.60-2.64 (m), 3.17-4.20 (m), 6.51 (d, *J* 8.2 Hz), 6.58-8.01 (m). ^{31}P{^{1}H} NMR ($CDCl_3$, 121.5 MHz) major isomer (75%): δ 10.5 (d, *J* 38 Hz), 27.4 (d, *J* 38 Hz); minor isomer (25%): δ 12.5 (d, *J* 39 Hz), 26.1 (d, *J* 39 Hz). IR (neat solid) ν_{max}/cm^{-1}: 3336 (ν_{N-H}), 3054, 2885, 1663 ($\nu_{C=O}$), 1536, 1436, 1094, 874, 818, 739, 691. Anal Calcd for $C_{54}H_{44}NOBrPdP_2$: C, 66.78; H, 4.52%. Found: C, 65.91; H, 4.58%.

[*PdBr(o-$C_6H_4CH_2CH_2COCH_3$){(S)-BINAP}] (**4**)*. Using a scale of 0.207 mmol in [$Pd_2(dba)_3$], the general procedure gave 243 mg (61%) of a pale yellow solid that contained traces of ether by ^{1}H NMR analysis (<5%). ^{1}H NMR ($CDCl_3$, 300 MHz) major + minor isomers: δ 2.20 (s, CH_3, minor isomer), 2.27 (s, CH_3, major isomer), 2.56-2.88 (m), 3.23 (td, *J* 12.5 and 5.0 Hz), 3.45-3.63 (m), 3.85 (td, *J* 12.7 and 3.7 Hz), 6.51 (d, *J* 8.7 Hz), 6.52-8.24 (m). ^{31}P{^{1}H} NMR ($CDCl_3$, 121.5 MHz) major isomer (59%): δ 9.7 (d, *J* 37.8 Hz), 27.0 (d, *J* 37.8 Hz); minor isomer (41%): δ 12.0 (d, *J* 39.7 Hz), 25.5 (d, *J* 39.1 Hz). IR (neat solid) ν_{max}/cm^{-1}: 3049, 1710 ($\nu_{C=O}$), 1573, 1556, 1502, 1478, 1436, 1309, 1158, 1092, 815, 745, 695. . Anal Calcd for $C_{59}H_{43}OBrPdP_2$: C, 67.83; H, 4.53%. Found: C, 67.93; H, 4.44%.

*[PdBr(o-$C_6H_4CH_2CH_2OH$){(S)-BINAP}] (**5**)*. Using a scale of 0.207 mmol in [$Pd_2(dba)_3$], the general procedure gave 302 mg (79%) of a pale brown solid that contained traces of ether by ^{1}H NMR analysis (<5%). ^{1}H NMR ($CDCl_3$, 300 MHz) major + minor isomers: δ 2.17 (t, *J* 5.4 Hz), 2.35 (t, *J* 5.7 Hz), 2.90-3.00 (m), 3.23-3.30 (m), 3.51-3.70 (m), 4.00-4.30 (m), 6.48-8.15 (m). ^{31}P{^{1}H} NMR ($CDCl_3$, 121.5 MHz) major isomer (55%): δ 10.2 (d, *J* 38.4 Hz), 22.7 (d, *J* 38.4 Hz); minor isomer (45%): δ 11.8 (d, *J* 39.1 Hz), 24.8 (d, *J* 39.1 Hz). IR (neat solid) ν_{max}/cm^{-1}: 3436 (ν_{O-H}), 3049, 1499, 1480, 1457, 1436, 1304, 1092, 1028, 820, 741, 670. Anal Calcd for $C_{52}H_{41}OBrPdP_2$: C, 67.24; H, 4.45%. Found: C, 67.17; H, 4.41%.

*[PdBr(o-$C_6H_4CH_3$){(S)-BINAP}] (**6**)*. Using a scale of 0.207 mmol in [$Pd_2(dba)_3$], the general procedure gave 333 mg (89%) of a pale yellow solid that contained traces of ether (<5%) and P(*o*-tolyl)$_3$ (<1%) by ^{1}H and ^{31}P NMR analysis. ^{1}H NMR ($CDCl_3$, 300 MHz) major (65%) + minor (35%) isomers: δ 2.57 (CH_3, minor isomer), 2.86 (CH_3, major isomer), 6.43 (s, br), 6.58-8.08 (m). ^{31}P NMR ($CDCl_3$, 121.5 MHz) major isomer (67%): δ 9.7 (d, *J* 38.5 Hz), 27.4 (d, *J* 38.4 Hz); minor isomer (33%): δ 10.9 (d, *J* 38.4 Hz), 24.5 (d, *J* 38.5 Hz). ^{31}P{^{1}H} NMR (C_6D_6, 121.5 MHz) major isomer (63%): δ 10.0 (d, *J* 37.8 Hz), 26.5 (d, *J* 37.8 Hz); minor isomer (37%): δ 10.7 (d, *J* 38.5 Hz), 23.5 (d, *J* 38.5 Hz). IR (neat solid) ν_{max}/cm^{-1}: 3054, 1588, 1561, 1499, 1478, 1436, 1318, 1308, 1092, 1027, 870, 820, 735, 697. Anal Calcd for $C_{51}H_{39}BrPdP_2$: C, 68.05; H, 4.37%. Found: C, 68.27; H, 4.33%.

*[PdBr(o-C_6H_4-iPr){(S)-BINAP}] (**7**).* Using a scale of 0.207 mmol in [$Pd_2(dba)_3$], the general procedure gave 183 mg (59%) of a pale yellow solid that was recrystallised from dichloromethane-pentane giving pale yellow needles. ^{1}H NMR ($CDCl_3$, 300 MHz) major isomer (87%) δ 0.75 (d, CH_3, *J* 6.9 Hz), 1.44 (d, CH_3, *J* 6.8 Hz), 3.75-3.85 (m, CH), 6.6-8.0 (m). ^{31}P{^{1}H} NMR ($CDCl_3$, 121.5 MHz) major isomer (87%): δ 12.0 (d, *J* 37.8 Hz), 26.6 (d, *J* 38.5 Hz); minor isomer (13%): δ 12.0 (d, *J* 39.1 Hz), 25.0 (d, *J* 39.7 Hz). IR (neat solid) ν_{max}/cm^{-1}: 3053, 2973, 2956, 2935, 2865, 1588, 1573, 1468, 1449, 1436, 1378, 1092, 1032, 1019, 822, 745, 727, 695. Anal Calcd for $C_{53}H_{43}BrPdP_2$: C, 68.58; H, 4.67%. Found: C, 67.16; H, 4.07%.

*[PdBr(o-C_6H_4Ph){(S)-BINAP}] (**8**).* Using a scale of 0.207 mmol in [$Pd_2(dba)_3$], the general procedure gave 233 mg (59%) of a pale pink solid that contained traces of ether by ^{1}H NMR analysis (< 5%). ^{1}H NMR ($CDCl_3$, 300 MHz) δ 5.62 (dd, 1H, *J* 11.5 and 8.7 Hz), 5.78 (s, br, 1H), 6.06 (s, br, 1H), 6.45-7.55 (m, 34 H), 7.74 (s, br, 2H), 8.01 (td, 1H, *J* 6.7 and 2.9 Hz), 8.37 (s, br, 1H). ^{31}P{^{1}H} NMR ($CDCl_3$, 121.5 MHz) major isomer (99%): δ 14.0 (d, *J* 40.1 Hz), 26.3 (d, *J* 39.0 Hz); minor isomer (1%): δ 11.4 (d, *J* 38.0 Hz), 25.8 (d, *J* 38.1 Hz). IR (neat solid) ν_{max}/cm^{-1}: 3053, 1586, 1569, 1478, 1436, 1304, 1096, 1019, 816, 741, 695. Anal Calcd for $C_{56}H_{41}BrPdP_2$: C, 69.99; H, 4.30%. Found: C, 69.59; H, 3.85%.

*[PdBr(o-$C_6H_4CH_2$CONHBn)(DPPF)] (**9**).* Using DPPF instead of (S)-BINAP, the general procedure gave 643 mg (79%) of a yellow solid that contained traces of ether by ^{1}H NMR analysis (< 5%). ^{1}H NMR ($CDCl_3$, 300 MHz) δ 3.00 (d, 1H, *J*15.2 Hz), 3.53 (s, 1H), 3.63 (s, 1H), 4.01 (d, 1H, *J* 14.7 Hz), 4.14-4-45 (m, 6H), 4.65 (s, 1H), 5.01 (s, 1H), 6.51-7-49 (m, 23 H), 7.89-8.15 (m, 6H). ^{31}P{^{1}H} NMR ($CDCl_3$, 121.5 MHz) δ 8.7 (d, *J* 32.4 Hz), 29.8 (d, *J* 31.7 Hz). ^{31}P NMR (C_6D_6, 121.5 MHz) δ 7.7 (d, *J* 32.4 Hz), 28.4 (d, *J* 31.7 Hz). IR (neat solid) ν_{max}/cm^{-1}: 3315 (ν_{N-H}), 3085, 3056, 2973, 2898, 2858, 1679 ($\nu_{C=O}$), 1574, 1534, 1505, 1482, 1434, 1301, 1275, 1264, 1167, 1098, 1036, 1025, 756, 737, 695. Anal Calcd for $C_{49}H_{42}NOBrFePdP_2$: C, 60.99; H, 4.39%. Found: C, 61.10; H, 4.43%.

*[PdBr(o-$C_6H_4CH_2{}^{13}$CONHBn)(DPPF)] (**9a**).* A solution of {[P(*o*-tolyl)$_3$]Pd[*o*-$C_6H_4CH_2{}^{13}$CON(H)Bn](Br)}$_2$ (10 mg, 0.007 mmol) and ddpf (9 mg, 0.016 mmol) in C_6D_6 (2 mL) was stirred at room temperature overnight in a glovebox. The solution was analyzed without isolation by ^{31}P and ^{13}C NMR spectroscopy. ^{31}P{^{1}H} NMR (C_6D_6, 121.5 MHz) δ 7.7 (d, *J* 32.3 Hz), 28.4 (d, *J* 31.7 Hz).^{13}C{^{1}H} NMR (C_6D_6, 75.4 MHz) δ ^{13}CO 174.4.

*[Pd(o-$C_6H_4CH_2CO^{15}$NHBn)(DPPF)] (**9b**).* A solution of {[P(*o*-tolyl)$_3$]Pd[*o*-$C_6H_4CH_2CO^{15}$N(H)Bn](Br)}$_2$ (20 mg, 0.014 mmol) and ddpf (20 mg, 0.036 mmol) in C_6D_6 (2 mL) was stirred at room temperature overnight into a glovebox. The solution was analyzed without isolation by ^{31}P NMR spectroscopy. ^{31}P{^{1}H} NMR (C_6D_6, 121.5 MHz) δ 7.7 (d, *J* 31.7 Hz), 28.4 (d, *J* 31.7 Hz).

General procedure for the preparation of [Pd(Ar)Br{P(o-tolyl)$_3$}]$_2$.[25] A purple solution of [$Pd_2(dba)_3$] (382 mg, 0.418 mmol), P(*o*-tolyl)$_3$ (510 mg, 1.68 mmol) and aryl bromide (1.02 mmol) in benzene (30 mL) was stirred at room temperature for 16 h. The solution was filtered through Celite, and the benzene was removed under vacuum. The oily residue was dissolved in ether (25 mL) and stirred at room temperature for 16 h. The resulting precipitate was filtered, washed with ether and dried under vacuum.

[PdBr(o-$C_6H_4CH_2$CONHBn){P(o-tolyl)$_3$}]$_2$. The general procedure gave 510 mg (87%) of a yellow solid that contained traces of ether by ^{1}H NMR analysis (< 5%). ^{1}H NMR ($CDCl_3$, 300 MHz, 50 °C) δ 1.47 (br), 2.38 (br), 3.60 (br), 4.49 (br), 6.57-7-45 (m). %). ^{31}P{^{1}H} NMR ($CDCl_3$, 300 MHz, 50°C) δ 31.3 (s br). IR (neat solid) ν_{max}/cm^{-1}: 3242 (ν_{N-H}), 3092, 3056, 1609 ($\nu_{C=O}$), 1449, 1283, 1202, 1164, 1028, 805, 753, 699. Anal Calcd for $C_{72}H_{70}N_2O_2Br_2Pd_2P_2$: C, 60.48; H, 4.93%. Found: C, 60.61; H, 4.77%.

[PdBr(o-$C_6H_4CH_2{}^{13}$CONHBn){P(o-tolyl)$_3$}]$_2$. The general procedure gave 466 mg (78%) of a yellow solid that contained traces of ether by ^{1}H NMR analysis (<5%). ^{1}H NMR ($CDCl_3$, 300 MHz, 50 °C) *d* 1.49 (br), 3.52 (br), 4.39 (br), 6.23-7-66 (m). %). ^{31}P{^{1}H} NMR ($CDCl_3$, 300 MHz, 50 °C) δ 31.3 (s br). IR (neat solid) ν_{max}/cm^{-1}: 3244 (ν_{N-H}), 3064, 1569 ($\nu_{C=O}$), 1449, 1337, 1283, 1200, 1133, 1028, 805, 753, 742, 699. Anal Calcd for $C_{71}{}^{13}CH_{70}N_2O_2Br_2Pd_2P_2$: C, 60.69; H, 4.94%. Found: C, 60.99; H, 4.94%.

[PdBr(o-$C_6H_4CH_2CO^{15}$NHBn) {P(o-tolyl)$_3$}]$_2$. The general procedure gave 305 mg (51%) of a yellow solid that contained traces of ether by ^{1}H NMR analysis (< 5%) %). ^{1}H NMR ($CDCl_3$, 300 MHz, 50 °C) δ 1.47 (br), 3.48 (br), 4.49 (br), 6.57-7-45 (m). %). ^{31}P{^{1}H} NMR ($CDCl_3$, 300 MHz, 50°C) δ 31.2 (s br).IR (neat solid) ν_{max}/cm^{-1}: 3220 (ν_{N-H}), 3058, 1603 ($\nu_{C=O}$), 1573, 1553, 1449, 1283, 1202, 1164, 1133, 1028, 805, 751, 741, 716, 700, 679. Anal Calcd for $C_{36}H_{35}{}^{15}$NOBrPdP: C, 60.40; H, 4.93%. Found: C, 61.61; H, 4.63%.

Syntheses of cyclometallated [Pd(o-$C_6H_4CH_2CONBn)L_2$]

*[Pd(o-$C_6H_4CH_2CONBn$){(S)-BINAP}] (**11**).* A mixture of [PdBr(*o*-$C_6H_4CH_2CONHBn$){(S)-BINAP}] (246 mg, 0.238 mmol) and NaO-*t*-Bu (32 mg, 0.33 mmol) in benzene (20 mL) was stirred at room temperature for 16 h. The solution was filtered through Celite, and concentrated to approximately 3 mL. Addition of hexane (40 mL) gave a precipitate that was filtered, washed with pentane and dried under vacuum to give 200 mg (88%) of a yellow solid that contained traces of pentane by ^{1}H NMR analysis (<5%). ^{1}H NMR (C_6D_6, 300 MHz) major + minor isomers: δ 3.00 (d, *J* 14.2 Hz), 4.01 (d, *J* 15.6 Hz), 4.20 (d, *J* 12.4 Hz), 5.24 (br), 6.18-8.16 (m). ^{31}P{^{1}H} NMR (C_6D_6, 121.5 MHz) major isomer (59%): δ 13.3 (d, *J* 34.8 Hz), 28.9 (d, *J* 36.0 Hz); minor isomer (41%): δ 12.3 (d, *J* 38.5 Hz), 30.3 (d, *J* 39.1 Hz). IR (neat solid) ν_{max}/cm^{-1}: 3054, 2960, 1594 ($\nu_{C=O}$), 1580, 1501, 1478, 1437, 1376, 1308, 1098, 1027, 814, 739, 697. Anal Calcd for $C_{59}H_{45}NOBrPdP_2$: C, 74.43; H, 4.77%. Found: C, 74.64; H, 4.88%.

*[Pd(o-$C_6H_4CH_2{}^{13}CONBn$){(S)-BINAP}] (**11a**).* $NaOCPh_3$ (8 mg, 0.028 mmol) was added to a solution of [(S)-BINAP]Pd[*o*-$C_6H_4CH_2{}^{13}CON(H)Bn$] (20 mg, 0.019 mmol) in C_6D_6 (2 mL) and the mixture was stirred at room temperature overnight in a glovebox. The solution was filtered through Celite and analyzed without isolation by ^{31}P and ^{13}C NMR spectroscopy. ^{31}P{^{1}H} NMR (C_6D_6, 121.5 MHz)) major isomer (57%): δ 13.3 (d, *J* 36.0 Hz), 28.8 (d, *J* 36.0 Hz); minor isomer (43%): δ 12.4 (d, *J* 36.6 Hz), 30.3 (d, *J* 36.6 Hz).^{13}C{^{1}H} NMR (C_6D_6, 75.4 MHz) d^{13}CO 174.7 and 175.8.

*[Pd(o-$C_6H_4CH_2CO^{15}NBn$){(S)-BINAP}] (**11b**).* $NaOCPh_3$ (8 mg, 0.028 mmol) was added to a solution of [(S)-BINAP]Pd[*o*-$C_6H_4CH_2CO^{15}N(H)Bn$] (20 mg, 0.019 mmol) in C_6D_6 (2 mL) was stirred at room temperature overnight in a glovebox. The solution was filtered through Celite and analyzed without isolation by ^{31}P spectroscopy. ^{31}P{^{1}H} NMR (C_6D_6, 121.5 MHz) major isomer (57%): δ 13.3 (d, *J* 36.0 Hz), 28.8 (dd, *J* 46.0 and 36.0 Hz); minor isomer (43%): δ 12.4 (d, *J* 38.5 Hz), 30.3 (dd, *J* 44.5 and 38.51 Hz).

*[Pd(o-$C_6H_4CH_2CONBn$)(DPPF)] (**10**).* A mixture of PdBr(*o*-$C_6H_4CH_2CONHBn$(DPPF) (200 mg, 0.207 mmol) and NaO-*t*-Bu (30 mg, 0.312 mmol) in benzene (20 mL) was stirred at room temperature for 16 h. The solution was filtered through Celite, and concentrated to approximately 3 mL. Addition of hexane (40 mL) gave a precipitate that was filtered, washed with hexane and dried under vacuum to give gave 125 mg (68%) of a yellow solid that contained traces of pentane by ^{1}H NMR analysis (<5%). ^{1}H NMR (C_6D_6, 300 MHz) δ 2.99 (d, 1H, *J* 15.4 Hz), 3.61 (d, 2H, *J* 7.9 Hz), 3.68 (d, 2H, *J* 1.0 Hz), 3.85 (d, 1H, *J* 9.6 Hz), 4.02-4.08 (m, 3H), 5.04 (d, 1H, *J* 12.3 Hz), 5.52 (dd, 1H, *J* 15.4 and 9.6 Hz), 6.50 (m, 2H), 6.85 (m, 4H), 6.97-7.47 (m, 19 H), 7.64 (m, 2H), 8.02-8.08 (m, 2H). ^{31}P{^{1}H} NMR (C_6D_6, 121.5 MHz) δ 10.0 (d, *J* 35.4 Hz), 25.4 (d, *J* 34.8 Hz). IR (neat solid) ν_{max}/cm^{-1}: 3054, 2960, 1594 ($\nu_{C=O}$), 1580, 1501, 1478, 1437, 1376, 1308, 1098, 1027, 814, 739, 670. Anal Calcd for $C_{49}H_{41}NOFePdP_2$: C, 66.57; H, 4.67%. Found: C, 65.84; H, 4.58%.

*[Pd(o-$C_6H_4CH_2{}^{13}CONBn$)(DPPF)] (**10a**).* $NaOCPh_3$ (11 mg, 0.028 mmol) was added to the solution of PdBr(*o*-$C_6H_4CH_2{}^{13}CONHBn$)(DPPF) (obtained *in situ* from the reaction of PdBr(*o*-$C_6H_4CH_2{}^{13}CONHBn$){P(*o*-tolyl)$_3$}]$_2$ (10 mg, 0.007 mmol) and dppf (9 mg, 0.016 mmol) in C_6D_6 (2 mL)) and stirred at room temperature for 16 h in a glove box. The solution was filtered through Celite and analyzed without isolation by ^{31}P and ^{13}C spectroscopy. ^{31}P{^{1}H} NMR (C_6D_6, 121.5 MHz) δ 10.1 (d, *J* 35.4 Hz), 25.4 (d, *J* 35.4 Hz). ^{13}C{^{1}H} NMR (C_6D_6, 75.4 MHz) δ ^{13}CO 174.4.

*[Pd(o-$C_6H_4CH_2CO^{15}NBn$)(DPPF)] (**11b**).* $NaOCPh_3$ (11 mg, 0.054 mmol) was added to the solution of PdBr(*o*-$C_6H_4CH_2CO^{15}NHBn$)(DPPF) (obtained *in situ* from the reaction of [PdBr(*o*-$C_6H_4CH_2CO^{15}NHBn$){P(*o*-tolyl)$_3$}]$_2$ (20 mg, 0.014 mmol) and dppf (20 mg, 0.036 mmol) in C_6D_6 (2 mL))and stirred at room temperature for 16 h in a glove box. The solution was filtered through Celite and analyzed without isolation by ^{31}P and ^{13}C spectroscopy. ^{31}P{^{1}H} NMR (C_6D_6, 121.5 MHz) δ 10.1 (dd, *J* 36.0 and 3.7 Hz), 25.4 (dd, *J* 47.6 and 35.4 Hz).

X-ray crystallography

Crystal Data and Structure Refinement for **1**

empirical formula	$C_{59}H_{46}BrNOP_2Pd$
fw	1033.22
crystal system	orthorhombic
space group	
unit cell dimensions	a = 22.0111(7) A^o, α = 90^o
	b = 23.8884(7) A^o, β = 90^o
	c = 11.7226(3) A^o, γ = 90^o
volume (A^{o3})	6163.9(3)
Z	4
μ (mm^{-1})	1.034
F(000)	2104
Temperature (K)	293(2)
θ range (ω scans) (deg)	1.26-23.26^o
no. of reflns collected	25425
no. of data/restr/params	8837/0/587
goodness-of-fit on F^2	1.063
R1/wR2 [$I > 2\sigma(I)$]	0.0706/0.1212
R1/wR2 (all data)	0.1015/0.1330
extinction coeff	0.00000(5)
max/min peaks (e/A^{o3})	0.530/-0.370

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Supplementary Information

Crystallographic data for the structure reported in this paper have been deposited with the Cambridge Data Center as Supplementary Publication No. CCDC- 219507 . These data can be obtained free of charge via www.ccdc.cam.ac.uk/conts/retrieving.html (or from the CCDC, 12 Union Road, Cambridge CB2 1EZ, UK; fax: +44 1223 336033; e-mail: deposit@ccdc.cam.ac.uk).

Electronic Supplementary Information

Inversion transfer experiments available as PDF file at http://jbcs.sbq.or.br

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