

Coordination Chemistry

Mechanistic Aspects of Aryl–Halide Oxidative Addition, Coordination Chemistry, and Ring-Walking by Palladium

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Abstract: This contribution describes the reactivity of a zerovalent palladium phosphine complex with substrates that contain both an aryl halide moiety and an unsaturated carbon–carbon bond. Although η^2 -coordination of the metal center to a C=C or C=C unit is kinetically favored, aryl halide bond activation is favored thermodynamically. These quantitative transformations proceed under mild reaction conditions in solution or in the solid state. Kinetic measurements indicate that formation of η^2 -coordination complexes are not nonproductive side-equilibria, but observable (and in several cases even isolated) intermediates en route to aryl halide bond cleavage. At the same time, DFT calculations

show that the reaction with palladium may proceed through a dissociation–oxidative addition mechanism rather than through a haptotropic intramolecular process (i.e., ring walking). Furthermore, the transition state involves coordination of a third phosphine to the palladium center, which is lost during the oxidative addition as the C–halide bond is being broken. Interestingly, selective activation of aryl halides has been demonstrated by adding reactive aryl halides to the η^2 -coordination complexes. The product distribution can be controlled by the concentration of the reactants and/or the presence of excess phosphine.

Introduction

Palladium-based catalysts are of prime importance for the formation of carbon-carbon and other bonds under mild and homogeneous reaction conditions.^[1] Numerous experimental^[2] and theoretical studies^[2b, 3] have been devoted to the mechanistic and application aspects of such reactions. Metal-mediated processes often require substrates with several reactive moieties, such as aryl halides and carbon-carbon multiple bonds. The relative reactivity of a metal center with diverse functional groups present in a system is one of the many factors that can play a role in the product distribution.^[4] A fundamental understanding of the mechanism of competing processes and the processes themselves might lead to the design of new, useful reactions with high selectivity. Studies related to the interaction and reactivity of halogenated and unsaturated substrates with transition metals can provide clues on how to improve the efficiency of palladium-catalyzed reactions.

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We have demonstrated that the reaction of [Ni(PEt₃)₄] and [Pt(PEt₃)₄] with halogenated substrates results in η^2 -coordination to a C=C or N=N moiety followed by an intramolecular aryl halide bond activation process.^[5] Despite the similar reaction pathways for these first- and third-row complexes, the rate-determining step is different. The nature of the aryl halide plays an important role in the platinum system, whereas the ring-walking of the metal center over the π system of the substrate is the slow step with nickel. These observations led to the selective activation by the nickel system of a strong aryl–Br bond in the presence of a much more reactive aryl–I bond^[5b] (bond dissociation energies (BDE) of Ph–Br=(80±2) kcal mol⁻¹[6]).

There is ample evidence for haptotropic arrangements in the literature.^[7] Intramolecular pathways were observed in the 1960s by Basolo^[8] and still generate much interest.^[9] Dötz and Jahr observed the haptotropic migration of a chromium complex along the extended π system of fused arenes.^[10] Weisheit et al. examined the related (4,4'-dibromotolane)platinum(0) diphoshine complex and observed an initial coordination to the central C=C bond followed by C-Br oxidative addition.^[11] Weak interactions between saturated hydrocarbons and metal complexes have been observed as well.^[4e, 12] However, the use of intramolecular reaction channels to selectively functionalize a compound is rare.^[13] Yokozawa and Yokoyama demonstrated that the nickel-catalyzed formation of π -conjugated polymers involves an intramolecular process coupled with selective aryl halide bond cleavage.^[14] Kiriy and co-workers observed the migration of a nickel(0) complex along a thiophene π -system in the Kumada catalyst transfer polycondensation of thiophenebased oligomers.^[15] Likewise, Nebra et al. observed the shift of a rhodium fragment between the arms of a bimetallic (1,3-bis-(thiophosphinoyl)indenyl)palladium complex across the ligand π system.^[16]

One of the questions that remain is whether the reaction of $[Pd(PEt_3)_4]$ with halogenated substrates will reflect that of platinum or nickel; will the rate-determining step be similar to the platinum or nickel system and can we control the selectivity of the reaction? In this study, we observed that η^2 -coordination of $[Pd(PEt_3)_2]$ to a C=C or a C=C moiety is kinetically favored and followed by a rate-determining aryl halide bond activation. This process proceeds quantitatively in solution and in the solid state (C-C bond formation by Pt⁰ in the solid state has been previously observed^[13]). Herein, we present a combined experimental and computational study that involves variable-

temperature NMR spectroscopy, competition/cross-over experiments, and density functional theory (DFT) calculations.

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Results and Discussion

The reaction of compounds 1 with an equimolar amount of [Pd(PEt₃)₄] in an organic solvent (e.g., toluene, THF, acetone) results in the quantitative formation of complexes 2 (Scheme 1). The formation of these complexes was carried out at temperatures below -30°C lest the reaction continue to oxidative addition products **3**. η^2 -Coordination of the metal center to the C=C or C=C moieties of compounds 1 is evident from the ¹H,¹³C{¹H}, and ³¹P{¹H} NMR spectroscopy data and the X-ray structure of 2^{Br} complex (Figure 1, left; the superscript identifies the halide and the subscript gives the bond order of the carbon-carbon bridge). Prolonged reaction times at elevated temperatures result in the quantitative formation of complexes 3 by insertion of the metal center into the aryl halide bond (Scheme 1). These complexes were isolated and characterized by using a combination of NMR spectroscopy, elemental analysis, and high-resolution mass spectroscopy. The palladium complexes obtained herein (see the Experimental Section) have similar spectroscopic features as observed for structurally related nickel and platinum complexes.^[5b,d] Van Koten reported the formation and physicochemical properties of a series of structurally similar nitrogenbased pincer complexes.^[17] In addition, the molecular structures of complexes $\mathbf{3}_{=}^{Br}$ and $\mathbf{3}_{=}^{Br}$ were unambiguously verified by single-crystal X-ray structure determination (Figure 1). Regardless of the nature of the aryl halide (Br, I) and unsaturated moiety (C=C, C=C), selective η^2 -coordination of the metal center to compounds 1, with release of two equivalents of PEt₃, is the kinetically preferred process. This process is followed by a slower transformation to afford the thermodynamically favored products of aryl halide bond activation (**3**).

The X-ray analysis of complex $\mathbf{2}_{\equiv}^{Br}$ reveals a metal-ligand arrangement that reflects some features of a metallocyclopropene system (Figure 1, top left).^[1c,18] The coordination of the



Scheme 1. Selective formation of palladium complexes 2 by η^2 -coordination of compounds 1 followed by metal insertion into the aryl halide bond (3).



Figure 1. ORTEP diagrams of complexes $2_{=}^{Br}$ (top left), $3_{=}^{Br}$ (top right) and $3_{=}^{Br}$ (bottom) with thermal ellipsoids set at the 50% probability level. Hydrogen atoms are omitted for clarity. Selected bond length [Å] and angles [°] for $2_{=}^{Br}$ (there are two molecules of $2_{=}^{Br}$ per asymmetric unit): Pd1–C7 2.060(2), Pd1–C8 2.064(2), Pd1–P1 2.3170(5), Pd1–P2 2.3170(5), C8–C7 1.282(3), C8–C9 1.448(3), C1–C7 1.453(3), C4–Br1 1.910(2); C7-Pd1-P2 146.36(6), C7-Pd1-C8 36.23(8), C7-Pd1-P1 109.27(6), C8-Pd1-P2 110.13(6), P2-Pd1-P1 104.37(2); for $3_{=}^{Br}$ (there are two molecules of $3_{=}^{Br}$ per asymmetric unit): Pd1–Br1 2.513(1), Pd1–P2 2.321(1), Pd1–P1 2.325(1), Pd1–C1 2.011(4), C6–C7 1.436(5), C7–C8 1.200(5), C8–C9 1.426(5); C1-Pd1-Br1 178.3(1), P2-Pd1-P1 171.20(4), C1-Pd1-P1 90.4(1); for $3_{=}^{Br}$: Pd1–Br1 2.515(1), Pd1–P2 2.322(2), Pd1–P3 2.316(3), Pd1–C1 1.997(9), C4–C7 1.46(1), C7–C8 1.33(1), C8–C9 1.44(1); C1-Pd1-Br1 175.4(2), P2-Pd1-P3 170.1(1), C1-Pd1-P3 89.2(2).

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bond (C7-C8=1.282 Å). This value falls between a triple and a double carbon-carbon bond. For example, the C=C bond length in trans-1,2-bis(4-pyridyl)ethylene is 1.333 Å,^[19] whereas the C=C bond length of complex $\mathbf{3}_{=}^{Br}$ is 1.201 Å (vide infra). Complex $\mathbf{2}_{=}^{Br}$ exhibits a nearly planar geometry around the metal center (mean deviation from the Pd1-P1-P2-C7-C8) plane of 0.0011 Å) and angles of 104.36 and 36.23° for P1-Pd1-P2 and C7-Pd1-C8, respectively. The aromatic rings of the ligand are bent away from the Pd by approximately 35°: C1-C7-C8 = 142.84° and C9-C8-C7 = 148.3°. One can pass a plane through the PdP_2C_4 core, and there are angles of 37.4 and 55.2° between this plane and planes through the C₆Br and Py rings, respectively. The main impetus behind this geometry is probably the dominant π backbonding. The structure of the oxidative addition products 3_{-}^{Br} and 3_{-}^{Br} show typical square-planar geometries around the d⁸ metal centers, which are directly σ bonded to the arene (Figure 1, top right).^[5b, 17] Formation of the arene-metal bond does not significantly affect the bond lengths of the ligand, in which the carbon-carbon bonds are in the appropriate range for a conjugated aromatic system.

Is the formation of the η^2 -coordination complexes **2** a nonproductive side-equilibrium or a step on the reaction coordinate? The formation of complexes **3** from the kinetic products (**2**) could involve either inter- or intramolecular pathways. It is plausible that the η^2 -coordination complexes (**2**) are in equilibrium with the free ligands (**1**) and [Pd(PEt_3)₂]. In time, such highly reactive 14-electron species would cleave the aryl halide bond and result in the formation of observed complexes **3**. Alternatively, the metal center could shift over the π -conjugated system of the ligand towards the aryl halide bond (i.e., ringwalking).^[5b, 15a, 20] In a third scenario, the kinetic products might rearrange by a cascade of reactions that involve the formation of transient bimetallic complexes.^[21]

Several observations point towards a concerted oxidative addition process as the rate-determining step for the bromo derivatives (i.e., reactions $2_{-}^{Br} \rightarrow 3_{-}^{Br}$ and $2_{-}^{Br} \rightarrow 3_{-}^{Br}$). We monitored the formation of thermodynamically favored complexes 3 by using ³¹P{¹H} NMR spectroscopy at various temperatures. The transformations of the iodo derivatives $(\mathbf{2}_{=}^{l} \rightarrow \mathbf{3}_{=}^{l} \text{ and } \mathbf{2}_{=}^{l} \rightarrow \mathbf{3}_{=}^{l})$ proceed under conditions ($T \le -48$ °C) at which the bromo derivatives $(\mathbf{2}_{=}^{Br}, \mathbf{2}_{=}^{Br})$ are stable. The reactivity differences are significant ($\Delta T \approx 60$ °C) and indicate that the rate-determining step for the transformations $2_-^{Br}{\rightarrow} 3_-^{Br}$ and $2_=^{Br}{\rightarrow} 3_=^{Br}$ are related to the cleavage of the aryl halide bond (c.f. BDEs of Ph-Br= (80 ± 2) kcal mol⁻¹ and Ph–I= (65 ± 2) kcal mol⁻¹).^[6] The η^2 -coordination of the metal center is not likely to be drastically affected by the electronic difference between the two halides (c.f. Hammett constant σ_p : I=0.18, Br=0.23).^[22] The solvent polarity does not affect the reaction kinetics (Table 1, entries 1, 2: $k_{\text{toluene}}/k_{\text{acetone}}$ for $\mathbf{2}_{=}^{\text{Br}} \rightarrow \mathbf{3}_{=}^{\text{Br}} \approx 1.1$ and entries 6, 7: $k_{\text{toluene}}/k_{\text{THF}}$ for $\mathbf{2}_{=}^{Br} \rightarrow \mathbf{3}_{=}^{Br} \approx 1.2$). These reactions are also barely affected by the presence of 0 to 10 equivalents of PEt₃ (Table 1, entries 4, 5: $k_2/$ k_{10} for $\mathbf{2}_{=}^{\mathbf{Br}} \rightarrow \mathbf{3}_{=}^{\mathbf{Br}} \approx 1.2$ and entries 6, 9: k_0/k_{10} for $\mathbf{2}_{=}^{\mathbf{Br}} \rightarrow \mathbf{3}_{=}^{\mathbf{Br}} \approx 1.0$). Therefore, it is plausible that a nonpolar, concerted transition state with two PEt₃ ligands bound to the metal center is involved in the slow step. Indeed, performing the reaction 2^{Br}_{-}

 $\mathbf{3}_{=}^{Br}$ in the presence of excess of tetrabutylammonium iodide resulted in the formation of complex $\mathbf{3}_{=}^{Br}$ (94%) as the major product. Only 6% halide exchange ($\mathbf{3}_{=}^{I}$) was observed by using ¹H and ³¹P{¹H} NMR spectroscopy, which could also have taken place after the formation of complex $\mathbf{3}_{=}^{Br}$. Some halide exchange (4%) was observed upon treatment of complex $\mathbf{3}_{=}^{Br}$ with tetrabutylammonium iodide under the same reaction conditions. This observation essentially rules out the formation of transient, cationic complexes. Formation of ionic bromide would have resulted in significant halide scrambling.^[23]

Table 1. Reaction rates of the formation of complexes 3 from complexes 2.						
Entry	Reaction	T [K]	[2] [тм]	PEt₃ [equiv]	Solvent	k [×10 ⁻⁵ s ⁻¹] ^[a]
1	$2^{Br}_{=} \rightarrow 3^{Br}_{=}$	297	74 74	2	[D ₈]toluene	6.1
3	$2 \xrightarrow{=} 3 \xrightarrow{=} 3$ $2 \xrightarrow{Br} 3 \xrightarrow{Br}$	297	19	2	[D ₈]toluene	5.8
4	$2^{Br}_{=} \rightarrow 3^{Br}_{=}$	291	19	2	[D ₈]toluene	3.3
5	$2^{\text{Br}}_{=} \rightarrow 3^{\text{Br}}_{=}$	291	19	10	[D ₈]toluene	2.7
6 7	2 →3 2 ^{Br} →3 ^{Br}	303	43 43	0	[D ₈]toluene THF	7.0 6.3
8	2 ^{Br} →3 ^{Br}	303	21	0	[D ₈]toluene	7.2
9	$2_{\equiv}^{\overline{B}r} \rightarrow 3_{\equiv}^{\overline{B}r}$	303	43	10	[D ₈]toluene	7.3
10	$2_{=}^{I} \rightarrow 3_{=}^{I}$	226	19	2	[D ₈]toluene	6.1
11	2'_→3'_	226	19	2	[D ₆]acetone	7.0
12	2'_→3'_ 2'_∖2'	226	19 74	10 2	[D ₈]toluene	6.5 6.2
14	$2 \xrightarrow{-} 3 \xrightarrow{-} 3$	220	74 19	2	[D ₈]toluene	4.9
15	2 ^I _→3 ^I _	235	19	2	[D ₆]acetone	3.9
16	2 ⁱ ₌ →3 ⁱ ₌	235	85	2	[D ₈]toluene	5.0
17	$2_{\equiv}^{I} \rightarrow 3_{\equiv}^{I}$	235	19	10	[D ₈]toluene	5.1
[a] These values were derived by using $^{31}P{^1H}$ NMR spectroscopy by using first-order linear fits with $R^2 > 0.99$.						

All four processes $(2 \rightarrow 3)$ are concentration independent (Table 2, entries 1, 3 and 6, 8) and obey first-order kinetics in η^2 -coordination complexes **2**. The activation parameters derived from Eyring plots (Figure 2) are listed in Table 2. The differences between the bromo $(\mathbf{2}_{-}^{Br}\rightarrow\mathbf{3}_{-}^{Br}, \mathbf{2}_{=}^{Br}\rightarrow\mathbf{3}_{=}^{Br})$ and iodo derivatives $(\mathbf{2}_{=}^{I} \rightarrow \mathbf{3}_{=}^{I}, \mathbf{2}_{=}^{I} \rightarrow \mathbf{3}_{=}^{I})$ reflects, as noted above, the large role of the halide in the overall process. The nearly identical activation parameters of the C=C $(\mathbf{2}_{=}^{Br}{\rightarrow}\mathbf{3}_{=}^{Br},\ \mathbf{2}_{=}^{I}{\rightarrow}\mathbf{3}_{=}^{I})$ and C=C $(\mathbf{2}_{=}^{Br} \rightarrow \mathbf{3}_{=}^{Br}, \mathbf{2}_{=}^{I} \rightarrow \mathbf{3}_{=}^{I})$ systems with the same halide indicate a similar reaction profile and that the character of these carboncarbon bonds does not play a significant role in controlling the overall reactivity. The near-zero entropy values further indicate that metal-ligand dissociation is not part of the rate-determining step. An intramolecular process or a dissociation step followed by a rate-determining oxidative addition could explain our observations. However, the negligible effect of the solvent polarity or the presence of PEt₃ rules against the formation of unsaturated palladium intermediates formed by a dissociation process. A process involving the formation of bimetallic complexes would most probably also be affected by both solvent polarity and by the presence of phosphine, and would likely not follow first-order kinetics in the metal complex. In addition, the quantitative thermolysis of complex 2_{-}^{Br}



Table 2. Activation parameters (in $[D_8]$ toluene) derived from the Eyring plots in Figure 2.						
	X=Br X=I					
	CH=CH	C≡C	CH=CH	C≡C		
	$2_{=}^{\text{Br}} {\rightarrow} 3_{=}^{\text{Br[a]}}$	$2_{\equiv}^{Br} \!$	$2_{=}^{I} \rightarrow 3_{=}^{I}$	$2^{I}_{\underline{=}}{\rightarrow}3^{I}_{\underline{=}}^{[d]}$		
ΔH^{\pm} [kcal mol ⁻¹]	23.5±1.9	22.7 ± 2.0	15.9±1.05	19.2±0.9		
ΔS^{*} [e.u.]	1.3 ± 6.6	-2.3 ± 6.8	-6.9 ± 4.6	4.3 ± 3.7		
$\Delta G^{+}_{_{298K}}$ [kcal mol ⁻¹]	23.1 ± 1.9	23.4 ± 2.0	16.2 ± 1.05	17.9 ± 0.9		
[a] <i>T</i> =284-301 K. [b] <i>T</i> =293-313 K. [c] <i>T</i> =213-239 K. [d] <i>T</i> =225-250 K.						



Figure 2. Eyring plots of the conversion of $2_{\pm}^{\text{Br}} \rightarrow 3_{\pm}^{\text{Br}}$ (red line, \bullet , $R^2 = 0.980$; 19 mM) and $2_{\pm}^{\text{Br}} \rightarrow 3_{\pm}^{\text{Br}}$ (black line, \oplus , $R^2 = 0.970$; 42.8 mM); $2_{\pm}^{\text{I}} \rightarrow 3_{\pm}^{\text{I}}$ (red line, \blacksquare , $R^2 = 0.987$; 19 mM) and $2_{\pm}^{\text{I}} \rightarrow 3_{\pm}^{\text{I}}$ (black line, \bowtie , $R^2 = 0.989$; 19 mM). ³¹P{¹H} NMR spectroscopy in [D₈]toluene was used for all experiments (Figure S1 in the Supporting Information).

as a powder at 40 °C to give complex $\mathbf{3}_{\equiv}^{\mathbf{Br}}$ also supports an intramolecular pathway. This relatively slow solid-state process takes 24 d to reach completion.

To unambiguously verify the presence of an intramolecular reaction channel, we used NMR spectroscopy to follow the conversion of the η^2 -coordination complexes (2) into complexes 3 in the presence of p-CF₃PhBr (4^{Br}) or p-CF₃PhI (4^I; see Scheme 2). The strongly electron-withdrawing CF₃ unit makes these substrates highly susceptible to activation by palladium. Plotting the $C_{Br} \ ^{13}\text{C}\{^1\text{H}\}\,\text{NMR}$ shifts versus the Hammett constant predicts that the aryl-Br and aryl-I bonds of compounds $\mathbf{4}^{\mathrm{Br}}$ and $\mathbf{4}^{\mathrm{I}}$ would be much more reactive than those of compounds 1 with the same halide (Figure S2 in the Supporting Information). Transfer of the metal center to compounds 4^{Br} and 4^{I} to afford complexes 5^{Br} and 5^{I} , respectively, was observed (15-35%) in parallel to the formation of complexes 3 (Table 3, entries 1, 3, 5, 7). Importantly, these competitive reactions are almost completely suppressed by the presence of 12 equivalents of PEt₃ (Table 3, entries 2, 4, 6, 8). Thus, this is a unique example in which the selectivity of aryl bond activation can be controlled simply by the addition of excess PEt₃. This clearly demonstrates that the two competing aryl halide bond activation processes proceed by different routes. Selective cleavage of a strong bond by a late-transition metal in the presence of a weaker one is rare.^[4h, 5b, 24] In addition, no metal transfer was



Scheme 2. Exclusive formation of complexes 3 (from 2) in the presence of compound 4 (X = Br or I). All experiments were performed in the presence of 12 equivalents of PEt₃.

Table 3. Crossover experiments for complexes 2 in the presence of p-
$CF_{3}PhX$ (X = Br (4^{Br}) or X = I (4^{I})) and varying concentrations of added PEt_{3}
(in [D_8]toluene at RT for \approx 10 h, see the Experimental section).

Entry	Reaction	[2] [тм]	[CF ₃ PhX] [тм]	PEt ₃ [equiv]	Ratio 3:5 [%]
1	$2^{Br}_{=} \rightarrow 3^{Br}_{=}$	8.5	5.7	0	84:16
2	$2^{Br}_{=} \rightarrow 3^{Br}_{=}$	8.5	5.7	12	100:0
3	$2^{Br}_{\equiv} \rightarrow 3^{Br}_{\equiv}$	8.3	4.3	0	70:30
4	$2^{Br}_{\equiv} \rightarrow 3^{Br}_{\equiv}$	8.3	4.3	12	100:0
5	$2^{I}_{=} \rightarrow 3^{I}_{=}$	7.9	4.3	2	73:27
6	$2^{I}_{=} \rightarrow 3^{I}_{=}$	7.9	4.3	12	100:0
7	$2_{\equiv}^{\mathbf{I}} \rightarrow 3_{\equiv}^{\mathbf{I}}$	8.0	4.3	2	66:34
8	$2^{I}_{\equiv} {\rightarrow} 3^{I}_{\equiv}$	8.0	4.3	12	97:3

observed during the formation of complex $\mathbf{3}_{=}^{Br}$ from $\mathbf{2}_{=}^{Br}$ in the presence of PhBr.

The cross-over of $[Pd(PEt_3)_2]$ with the more reactive 4^{Br} and 4^{I} might involve PEt₃ dissociation from the η^2 -coordination complexes (2) followed by reaction of compounds 4^{Br} or 4^{I} with transient unsaturated species. Formation of complexes 3 is observed in high yield (>97%) by blocking such a potential intermolecular pathway with the excess of PEt₃, whereas an intramolecular route would not be affected (Table 3, entries 2, 4, 6, 8).

This hypothesis is further supported by the reactivity of complex 6, which does not contain an aryl halide moiety (Scheme 3). This complex was prepared in situ by the addition of compound 7 to [Pd(PEt₃)₄]. The subsequent reaction with CF₃PhBr (4^{Br}) in the presence of PEt₃ resulted in quantitative formation of complex 5^{Br} and compound 7. Following the formation of **5**^{Br} (Figure 3), second-order kinetics are observed for this reaction $(6 + 4^{Br} \rightarrow 5^{Br} + 7)$, which is significantly slowed (by \approx 3) by the presence of excess PEt₃. These observations imply that the $2 \rightarrow 3$ transformations involve a different pathway, in which we hypothesize that the [Pd(PEt₃)₂] moiety ring-walks from the C=C or C=C moiety through a haptotropic rearrangement followed by metal insertion into the aryl halide bond. This latter step is rate determining and proceeds via a nonpolar concerted transition state for the aryl-bromide systems ($\mathbf{2}_{-}^{\mathtt{Br}}
ightarrow$ $\mathbf{3}_{=}^{\mathrm{Br}}, \mathbf{2}_{=}^{\mathrm{Br}} \rightarrow \mathbf{3}_{=}^{\mathrm{Br}}$). Wu et al. observed their nickel(0) catalysts jumping between adjacent, but nonconjugated, thiophene rings during Grignard metathesis chain-growth polymerization of poly(bithienylmethylene)s.^[25] It is conceivable that something similar is happening here and is suppressed by the added phosphine.



Scheme 3. Cross-over reaction of complex 6 with 4^{Br}.



Figure 3. Phosphine effect on the palladium transfer reaction: $6 + 4^{Br} \rightarrow 5^{Br} + 7$ with $1/[5^{Br}]$ as a function of time. The ³¹P{¹H} NMR spectroscopy follow-up measurements were performed in [D₈]toluene at 273 K in presence of two equivalents of PEt₃ (blue line, $k = 1.4 \times 10^{-4} \text{ m}^{-1} \text{ s}^{-1}$, $R^2 = 0.994$) and in the presence of 12 equivalents of PEt₃ (red line, $k = 3.9 \times 10^{-5} \text{ m}^{-1} \text{ s}^{-1}$, $R^2 = 0.988$).

To get a better understanding of the reaction mechanism, the reaction was studied computationally at the CP-CCSD(T)/cc-pVDZ-PP + $\Delta E^{SMD}_{MO6/TZVP}$ //DF-M06-L_{D3}/def2-SVP level of theory (see the Computational Methods section for full details), in which frequencies were scaled by 0.9958 as recommended by Kesharwani et al.^[26] Following convention, free energies are

typically given at "standard state" (i.e., 1 atm at 298.15 K); the corrections for concentration (ΔG_{corrr} see the Computational Details section for details) are given in Table S1 for typical concentrations used experimentally (i.e., 19 and 74 mм at 298.15 K). Table 4 lists key energies at 298.15 K during the reaction, whereas other experimentally used temperatures are considered in Table S2 in the Supporting Information. For complexes $\mathbf{2}_{=}^{Br}$ and $\mathbf{2}_{=}^{Br}$, the optimized complexes and transition states along the reaction pathway are shown in Figures 4 and 5, respectively; the iodo analogues are very similar in appearance.

As noted above, there are two conceivable reaction mechanisms. The metal center can ring-walk from the C=C/C=C bond along the ligand π system to arrive at the C-X bond to be activated, or it can dissociate from the C=C/C=C bond, either as-is (i.e., as [Pd(PEt₃)₂]) or with the assistance of one to two free phosphine ligands. In the second option, the free metal center would "float" around in solution until it encounters a C-X bond to react with. Key energies along each pathway are given in Table 4 and the various structures are depicted in Scheme 4. For all four systems, **TS(9-3)** is significantly lower in energy than **TS(2-3)** within the temperature range of 225 to 403 K. See Supporting Information (Table S2) for free energies at different temperatures. Note that although **TS(9-3)** increases with temperature, **TS(2-3)** decreases, albeit only very slightly (c.f. \approx -0.3 kcal mol⁻¹ for **TS(2-3)** versus \approx 4 kcal mol⁻¹ for **TS(9-3)** over this temperature range). Part of this is because of the much weaker coordina-

Table 4. Key energies $(\Delta G_{296,sol} \text{ [kcalmol}^{-1}], \text{CP-CCSD(T)/cc-pVDZ-PP} + \Delta E_{M06/TZVP}//DF-M06-L_{03}/def2-SVP)$ along the possible pathways for oxidative addition from complexes **2**. Energies are relative to **2** and are not corrected for concentration (see Table S1 in the Supporting Information).

	$2_{=}^{\mathrm{Br}}$	$2_{=}^{I}$	2 ^{Br} ≘	2 ^I _≡
TS(9–3)	22.8	17.5	21.7 (23.6) ^[a]	16.5 (17.6) ^[a]
TS(2–3)	31.7	24.1	30.9	22.5
TS(2–1)	22.2	23.2	34.9	35.5
9	1.3 ^[b]	-4.3 ^[b]	10.2	6.2
TS(2–8)	10.2	10.4	27.7	27.4
8	9.1	19.9	17.7	15.8
$2 \rightarrow 1 + 11^{2}$	20.3	20.9	18.2	19.0
$2 \rightarrow 10 + PEt_3$	26.6	32.4	21.0	20.6
$2 + PEt_3 \rightarrow 1 + 11^3$	0.1	0.7	-1.9	-1.1
$2 + 2 PEt_3 \rightarrow 1 + 11^4$	-1.2	-0.5	-3.2	-3.4
3	-21.3	-22.6	-21.7	-23.2

[a] Including the exergonic dissociation of PdP_3 . [b] Third phosphine not coordinated (see text).



Figure 4. DFT-optimized structures for the reaction of bromostilbazole 2_{\pm}^{Br} ; for clarity, the Br superscript and = subscript are not shown. The iodostilbazole analogues are very similar.

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Figure 5. DFT-optimized structures for the reaction of bromotolan 2_{\pm}^{Br} ; for clarity, the Br superscript and \pm subscript are not shown.

tion of Pd to an arene π system than Ni or Pt (see below for discussion). Previous studies on the related platinum and nickel complexes^[5b,d] show a preference for ring-walking over dissociation of the metal fragment. The weaker coordination to the aromatic π system means that the metal center is more likely to dissociate and coordinate a third phosphine, and in all four systems this is a favorable process on par with returning to the central C=C or C=C bond (c.f. 8 and $2 + \text{PEt}_3 \rightarrow 1 + 11^3$ in Table 4). As indicated for **TS(9–3)** in Table 4, the activation barrier is not necessarily from the bridge complexes (2) but in certain cases from $1 + 11^3$. In cases for which the latter is exergonic, one needs to subtract this energy from the transition state (i.e., reaction barrier) height.

Coordination of the palladium center to the ligands (1) seems to be significantly weaker than coordination of nickel or platinum,^[5b,d] and this is would appear to have a dramatic influence on the reaction chemistry. The coordination of a metal center to a π bond was examined for the model [M(PH₃)₂] (M = Ni, Pd, Pt) systems with ethylene, acetylene, and benzene. From the bond orders (BOs; Table S3 in the Supporting Information), it is clear that coordination of a metal center to an arene (i.e., formation of an η^2 -C₆H₆ complex) is less favorable



Scheme 4. Structures in the DFT study in which the wavy bond indicates variation in the bridging bond (i.e., $C \equiv C$ or CH = CH) and X = Br or I.

than coordination to a C=C or C=C bond (in this order). Likewise, the BO is lower for Pd than for Pt or Ni; conversely, the BO of the C=C/C=C bond is higher for Pd than for the other two metals, and in the case of benzene approaches the BO of free benzene. In fact, the BOs barely (if at all) reflect the formation of a Pd–C bonds in the $(\eta^2$ -arene)Pd complexes. In addition, the M-C bonds are stronger in the acetylene complexes than in the ethylene complexes and are weakest in the benzene complexes. In the benzene-Pd complex the bonds are very weak, and this is reflected in the fact that the energies of 8, in which the metal is bound to the phenyl ring (with the exception of 8^{Br}), are close to the bridge-

dissociation energies. From the estimates of the importance of all donor \rightarrow acceptor interactions in the natural bond order (NBO) basis (Table S4 in the Supporting Information), the importance of the $L \rightarrow M$ and $M \rightarrow L$ interactions are an order of magnitude smaller for the benzene complexes than for ethylene or acetylene. Moreover, note that the $L \rightarrow M$ interactions involve the metal s orbital; this orbital is much higher in energy (Table S5 in the Supporting Information) for Pd than for Ni or Pt. As noted above, metal coordination to acetylene is stronger than to ethylene. This is reflected in the results for the stilbazole $(\mathbf{1}_{-}^{X})$ and tolan $(\mathbf{1}_{-}^{X})$ systems. Although there is little difference in the dissociation energies of either 11³ or 11⁴ from the bridge complexes (2), the transition states for 11³ dissociation (TS(2-1)) and transfer to the ring (TS(2-8)) are significantly higher in the tolan systems. This reflects the need to break the stronger Pd-acetylene bond. This mirrors previous experimental observations^[27] and the strength of the platinum-ligand bond must in part be ascribed to relativistic effects.^[28]

Should the coordination complexes 2, 9, and 10 be described as dative complexes (i.e., with a $\| \mathop{\rightarrow} \mathsf{Pd}$ bond) or as metallacycles? These are the two extremes of the Dewar-Chatt-Duncanson model of alkene and acetylene complexes,^[29] whereas most complexes lies somewhere in the middle. If one considers the bond lengths of these complexes (Tables S8-S11 in the Supporting Information) or the bond indices of the model complexes (Table S3 in the Supporting Information), one notes that, for palladium, the coordinated C=C/C=C bonds are intermediate between these two extremes. From the bond orders of the model complexes, nickel and platinum lie much further towards the metallacycle description. In the benzene coordination complexes (8 and the model complexes), there is much less loss of C=C bonding character and these complexes probably are best described as dative complexes rather than as metallacycles.

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Dissociation of PdP₂ from **2** is not favorable and in all four cases involves reaction energies of $\Delta G_{298} \approx 18$ to 21 kcalmol⁻¹ (Table 4). For the stilbazole systems, there is a barrier slightly higher in energy than the products, but the more strongly bound tolan ligands have a considerably higher dissociation barrier. This reflects the stronger coordination of acetylene to a metal center than ethylene (see above). However, this dissociation process can perhaps be assisted by coordination of an additional, third phosphine ligand prior to dissociation. For the tolan systems, tris-phosphine complexes (9) were found, although their formation is endergonic (Table 4), whereas in the stilbazole systems the third phosphine will not remain coordinated to the metal center. In the model Pd-acetylene and Pdethylene complexes, the $M \rightarrow L$ interactions are very similar, yet in the former there are significantly stronger $L \rightarrow M$ interactions (Table S4 in the Supporting Information). One would thus expect that the increased electron density on the metal center would make coordination of the third phosphine less favorable. On the other hand, the acetylene can accept more electron density than ethylene, which thereby facilitates coordination of the third phosphine. However, if one considers the orbital energies of the model Pd complexes (Table S5 in the Supporting Information), one notes that the orbitals in the acetylene complex are systematically lower in energy and thus closer to the energy of the lone pair on the phosphine (for PH₃, $E_{HOMO} = -6.859$ eV, primarily composed of the lone pair on P); this would result in a better electronic interaction and, therefore, $\mathbf{9}_{=}^{\mathbf{X}}$ complexes can be found even though phosphine coordination is unfavorable. Nonetheless, the dissociation of 11^3 is practically isoergonic relative to **2**. For the stilbazole complexes, this reaction is slightly endergonic, consistent with the observation that 2 are isolated experimentally. For the tolan systems, the energies are slightly exergonic or endergonic depending on the solvation approximation used (SMD or $\Delta E^{\text{SMD}}_{\text{MO6/TZVP'}}$ see the Computational Methods section for details), which clearly highlights the small error one must remember exists even with the best computational methods. In addition, if one considers the correction for concentration (Table S1 in the Supporting Information), then these reactions are slightly endergonic; this is appropriate because the bridge complexes (2) are observed experimentally and, in one case $(2_{=}^{Br})$, isolated at low temperatures.

For cases in which complexes **2** are thermalized in the absence of phosphine, even though a phosphine-assisted dissociative mechanism is favored, a reaction may still be possible. For the iodo complexes, **TS(2–3)** may still be energetically achievable (Table 4). It is also possible that complexes **2** could lose a phosphine ligand, which would then assist another molecule of **2** to react. The energies for this process (Table 4) show that this is possible for the tolan complexes, but not for the stilbazole complexes. This is consistent with the stronger L \rightarrow M donation in the tolan complexes, which would help stabilize the complex when the phosphine dissociates.

Even though the experiments indicate that a dissociative mechanism is less likely (no effect of the concentration of the phosphine or complex on the reaction rate), it is still possible that the free 11³ moiety does not wander too far from its stil-

bazole or tolan ligand due to weak π interactions with the aromatic π system or because of the solvation cage. When *p*-CF₃PhBr (**4**^{Br}) or *p*-CF₃PhI (**4**^I) is added to the reaction mixture (i.e., the crossover experiments), some crossover is observed (16–34%; see Table 3). This is consistent with the dissociative mechanism found, but does not explain why crossover is suppressed when a large excess of phosphine is added.

In a previous study on the Sonogashira reaction, it was found that perfluoroaryl halides may react in an S_NAr fashion with phosphines to give P^{V} products akin to oxidative addition.^[30] This was also observed experimentally by Dardonville and Brun when they reacted $(p-BrPh)_2CO$ with $(n-C_5H_{11})_3P$ in toluene at reflux.^[31] With the more activating CF_3 group ($\sigma_p =$ 0.54 for CF₃ and 0.43 for COPh^[22]), one might expect the reaction of 4 with the smaller phosphine to be faster at lower temperatures. When large quantities of phosphine were added to the reaction mixture, the crossover of the stilbazole/tolan complexes was suppressed, and one possible explanation could be that the reaction of 4 with the free phosphine would sequester it and prevent its reaction with the Pd complex. The reaction of PhX and $p\text{-}\mathsf{CF}_3\mathsf{PhX}$ (X = Br, I) with PEt_3 was examined (Table S6 in the Supporting Information). Oxidative additionlike transition states were found for each aryl halide. Although these transition states are too high for the reaction to be feasible at room temperature, the reactions in each case are exergonic, so if such a reaction were to occur, through a different, yet-to-be-determined mechanism, then the aryl halide would be sequestered from the reaction and could not react with the palladium complex. In cases in which a large excess of phosphine is added, the sequestering of the aryl halide would be faster and, therefore, in this case crossover would not be observed. Nevertheless, when p-CF₃PhX and PEt₃ are mixed under the reaction conditions, no reaction is observed.

Summary and Conclusions

The reactivity towards stilbazole-based ligands of the final member of the Group 10 [M(PEt₃)₄] family has been explored. Previous studies on platinum and nickel systems have been reported. $^{\scriptscriptstyle [5b,d]}$ In all three cases, the metal center first coordinates to an unsaturated moiety (C=C, N=N, or C=C) prior to the activation of an aryl-Br or aryl-I bond.^[5a,b,d] In contrast to platinum and nickel, the coordination of palladium to the ligand $\boldsymbol{\pi}$ system is weak and this has a significant impact on the complex reactivity. Theoretical studies on the reactivity indicate a phosphine-assisted dissociation-reassociation mechanism via a transition state with three phosphine ligands on the metal center. This transition state is special in that three phosphines are coordinated to the metal center, whereas other related systems typically only involve two. However, the experimental data points towards a ring-walking-or at least a nondissociative-process; the rate of the reaction is independent of the concentration of the complex or phosphine in the system. The reason for this apparent discrepancy is not obvious, but it highlights the complexity of modeling the processes involved in aryl halide bond activation. Despite the generally similar behavior of the three metals, varying reactivity is observed in this



system, which is closely related to the strength and nature of the metal–ligand interaction, particularly with the ligand π system, and it is the middle member of this family that behaves differently from its two brothers.

Experimental Section

General procedures

All reactions were carried out in an N₂-filled M. Braun glovebox with H₂O and O₂ levels <2 ppm. Solvents were reagent grade or better and dried, distilled, and degassed before being introduced into the glovebox, in which they were stored over activated 4 Å molecular sieves. Ligands 1, 7, complex $\mathbf{3}_{=}^{Br}$, and [Pd(PEt₃)₄] (11⁴) were prepared according to published procedures.^[32]

Analysis

Mass spectrometry was carried out by using a Micromass Platform ZQ 4000 instrument, a Waters Micromass GCT Premier mass spectrometer, or a Q-TOF Waters-Micromass high-resolution mass spectrometer. Elemental analyses were performed by H. Kolbe, Mikroanalytisches Laboratorium, Germany. The ¹H, ¹³C{¹H}, ¹⁹F{¹H}, and ³¹P{¹H} NMR spectra were recorded at 400.19, 100.6, 376.48, and 161.9 MHz, respectively, by using a Bruker AMX 400 NMR spectrometer or at 500.132, 125.77, 470.5, and 202.46 MHz, respectively, by using a Bruker Avance 500 NMR spectrometer. All chemical shifts (δ) are reported in ppm and coupling constants (J) in Hz. The ¹H and ¹³C{¹H} NMR chemical shifts are reported relative to tetramethylsilane. ³¹P{¹H} NMR chemical shifts are given relative to 85% H_3PO_4 in D_2O at $\delta = 0.0$ (external reference), with shifts downfield of the reference considered positive. ¹⁹F{¹H} NMR spectra were referenced to an external standard of C_6F_6 at $\delta\!=\!-162.9\,\text{ppm}.$ All measurements were carried out at 298 K unless stated otherwise. Assignments in the ¹H and ¹³C{¹H} NMR spectra were made by using ¹H{³¹P} and ¹³C-DEPT-135 NMR spectroscopy.

Formation of 2^{Br}₌

[Pd(PEt₃)₄] (30 mg, 0.052 mmol) was dissolved in [D₈]toluene (0.3 mL) and loaded into a 5 mm screw-cap NMR tube. Subsequently, a solution of (E)-4-(4-bromostyryl)pyridine $(1_{=}^{Br}; 14 \text{ mg},$ 0.054 mmol) in $[D_8]$ toluene (0.4 mL) was added at -80 °C. The tube was immediately sealed, shaken, and transferred into the precooled NMR machine at -80 °C. Quantitative formation of complex 2_{-}^{Br} and PEt₃ (2 equiv) was observed by using ³¹P{¹H} NMR spectroscopy. This compound is stable in solution for at least 10 h at 0°C. Compound 2^{Br}_{-} was isolated by removing all the volatiles in vacuo at 0 $^{\circ}$ C and washing the residue with cold pentane (2 mL, -40 $^{\circ}$ C) to give a light yellow powder (96% yield). Performing this reaction at +11 °C also resulted in the quantitative formation of complex 2^{Br}₋. However, prolonged reaction times at this temperature resulted in the formation of complex $\mathbf{3}_{=}^{Br}$ (e.g., 49% conversion after 17.5 h). ¹H NMR ([D₆]acetone, 0 °C): $\delta = 8.12$ (d, ³J(H,H) = 5.8 Hz, 2 H; PyrH), 7.24 (d, ³J(H,H) = 8.4 Hz, 2H; ArH), 7.13 (d, ³J(H,H) = 7.6 Hz, 2H; ArH), 6.99 (d, ${}^{3}J(H,H) = 4.7$ Hz, 2H; ArH), 4.49 (m, ${}^{3}J(P,H) =$ 23.2 Hz, ³J(P,H)=6.5 Hz, ³J(H,H)=6.1 Hz, 1 H; CH=CH), 4.36 (m, ³J(P,H) = 22.6 Hz, ³J(P,H) = 6.4 Hz, ³J(H,H) = 7.0 Hz, 1 H; CH=CH), 1.42 (m, 12H; PCH₂CH₃), 0.88 ppm (m, 18H; PCH₂CH₃); ¹³C{¹H} NMR ([D₆]acetone, 0 °C): δ = 154.4 (C_a, s), 149.3, 146.2 (C_a, s), 131.1, 126.5, 119.1, 115.3 (C_q; C–Br), 59.9 (dd, ${}^{2}J(P,C) = 25.8$ Hz, ${}^{2}J(P,C) = 3.9$ Hz; CH=CH), 59.5 (dd, ²J(P,C) = 23.3 Hz, ²J(P,C) = 5.0 Hz; CH=CH), 18.7 (m; PCH₂CH₃), 9.7 ppm (m; PCH₂CH₃); ${}^{31}P{}^{1}H{}$ NMR ([D₈]toluene, 0 °C): AB system: δ_A = 13.5 ppm (1 P, ²J(P,P) = 16.1 Hz), δ_B = 12.0 ppm (1 P, ²J(P,P) = 16.0 Hz); HRMS (FD-TOF): *m/z* calcd for C₂₅H₄₀BrNP₂Pd: 603.0851; found: 603.0842.

Formation of 2¹

[Pd(PEt₃)₄] (8.0 mg, 0.014 mmol) was dissolved in [D₈]toluene (0.3 mL), loaded in a 5 mm screw-cap NMR tube equipped with a septum, and cooled to -80° C. Subsequently, a solution of (E)-4-(4-iodostyryl)pyridine $(1_{=}^{1}; 4.0 \text{ mg}, 0.013 \text{ mmol})$ in $[D_{8}]$ toluene (0.4 mL) was added dropwise. The tube was immediately shaken and transferred into a precooled (-80 °C) NMR machine. ${}^{31}\mathsf{P}\{{}^{1}\mathsf{H}\}\,\mathsf{NMR}$ spectroscopy indicated the quantitative formation of complex $\mathbf{2}_{_{=}}^{I}$ after ≈ 5 min. Performing this reaction at $-47\,^{\circ}\text{C}$ also resulted in the formation of complex $\mathbf{2}_{=}^{l}$, which selectively converted to complex 3^{I}_{-} (see below). Therefore, complex 2^{I}_{-} was characterized by using NMR spectroscopy in the presence of PEt₃ (2 equiv). ¹H NMR ([D₆]acetone, -80° C): $\delta = 8.57$ (brs, 1H; PyrH), 8.11 (brs, 2H; PyrH), 7.82 (d, J=7.8 Hz, 1H; PyrH), 7.59-7.43 (brm, 2H; ArH), 7.00 (brs, 2H; ArH), 4.45 (m, 1H; CH=CH), 4.34 (m, 1H; CH=CH), 1.52-1.42 (m, 12H; PCH₂CH₃), 0.87 ppm (m, 18H; PCH₂CH₃); ³¹P{¹H} NMR ([D₈]toluene): AB system: $\delta_A = 13.43$ ppm $(1 \text{ P}, {}^{2}J(\text{P},\text{P}) = 17.2 \text{ Hz}), \delta_{\text{B}} = 12.10 \text{ ppm} (1 \text{ P}, {}^{2}J(\text{P},\text{P}) = 17.2 \text{ Hz}).$

Formation of $2_{=}^{Br}$

A solution of $[Pd(PEt_{3})_{4}]$ (121 mg, 0.21 mmol) in THF (4 mL) was slowly added to a stirred solution of 4-((4-bromophenyl)ethynyl)pyridine ($1_{=}^{Br}$; 54 mg, 0.21 mmol) in THF (3 mL). All volatiles were removed under vacuum after 15 min. Washing the residue with pentane (1 \times 3 mL) afforded complex $\mathbf{2}_{=}^{Br}$ (80% yield). Subsequently, the yellow solid was dissolved in Et₂O (1 mL), followed by the addition of pentane (3 mL), and allowed to crystallize at $-30 \degree$ C under N₂. ¹H NMR ([D₆]acetone): $\delta = 8.39$ (d, ³J(H,H)=6.1 Hz, 2H; PyrH), 7.45 (d, ³J(H,H) = 8.4 Hz, 2H; ArH), 7.22 (d, ³J(H,H) = 8.1 Hz, 2H; ArH), 7.13 (d, ³J(H,H) = 7.0 Hz, 2H; ArH), 1.56–1.68 (m, 12H; PCH₂CH₃), 0.97–1.07 ppm (m, 18H; PCH₂CH₃); ¹³C{¹H} NMR $([D_6]acetone): \delta = 149.3 (s), 147.0 (dd, C_{q'} {}^3J(P,C) = 14.3 Hz, {}^3J(P,C) = 8.6 Hz), 136.5 (dd, C_{q'} {}^3J(P,C) = 14.0 Hz, {}^3J(P,C) = 8.8 Hz), 131.1 (s), 129.5 (s), 124.4 (dd, C_{q'} {}^2J(P,C) = 66.7 Hz, {}^2J(P,C) = 4.1 Hz; C=C), 121.3$ (s), 121.0 (dd, $C_{q'}$ ²*J*(P,C) = 4.1 Hz; C=C), 118.1 (s, C_{q}), 19.3 (dd, ¹*J*(P,C) = 29.8 Hz, ³*J*(P,C) = 15.7 Hz; PCH₂CH₃) 8.5 ppm (d, ²*J*(P,C) = 9.1 Hz; PCH₂CH₃); ³¹P{¹H} NMR ([D₈]toluene): $\delta = 16.75$ (d, 1 P, $^{2}J(P,P) = 5.1$ Hz), 15.29 ppm (d, 1P, $^{2}J(P,P) = 5.0$ Hz); HRMS (FD-TOF): *m*/*z* calcd for C₂₅H₃₉NBrP₂Pd: 601.0695; found: 601.0679 [*M*+H]⁺; elemental analysis calcd (%): C 49.97, H 6.37, N 2.33; found: C 50.65, H 6.17, N 2.49.

Formation of $2_{=}^{I}$

A solution of $[Pd(PEt_{3})_{4}]$ (9.0 mg, 0.016 mmol) in $[D_{8}]$ toluene (0.3 mL) was slowly added to a stirred solution of 4-((4-iodophenyl)ethynyl)pyridine ($1^{1}_{=}$; 4.7 mg, 0.015 mmol) in $[D_{8}]$ toluene (0.4 mL) at -60 °C. The quantitative formation of compound $2^{1}_{=}$ was observed after \approx 20 min by using ³¹P{¹H} NMR spectroscopy at this temperature. No intermediates were observed. ¹H NMR ([D_{8}]toluene, -63 °C): δ = 8.49 (d, ³J(H,H) = 5.9 Hz, 2 H; PyrH), 7.27 (d, ³J(H,H) = 8.2 Hz, 2 H; ArH), 7.05 (d, ³J(H,H) = 5.5 Hz, 2 H; ArH), 6.98 (d, ³J(H,H) = 8.1 Hz, 2 H; ArH), 1.25-1.16 (m, 12 H; PCH₂CH₃), 0.82-0.76 ppm (m, 18 H; PCH₂CH₃); ¹³C{¹H} NMR ([D_{6}]acetone, -63 °C): δ = 149.2, 146.8 (dd, br, C_q), 137.1, 136.4 (dd, br, C_q), 129.8, 125.1 (dd, C_q, ²J(P,C) = 68.3 Hz, ²J(P,C) = 4.0 Hz; C=C), 122.1 (dd, C_q, ²J(P,C) = 64.8 Hz, ²J(P,C) = 4.2 Hz; C=C), 121.5, 89.3 (s, C_q; C–I), 18.6

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(m, PCH₂CH₃), 8.5 ppm (m, PCH₂CH₃); ³¹P{¹H} NMR ([D₈]toluene): δ = 16.01 (d, 1 P, ²J(P,P) = 4.8 Hz), 14.6 ppm (d, 1 P, ²J(P,P) = 4.8 Hz).

Formation of 3^{Br}_

This is a modification of a previously reported procedure.^[32b] A solution of $[Pd(PEt_3)_4]$ (39 mg, 0.067 mmol) in THF (2 mL) was added to a solution of (E)-4-(4-bromostyryl)pyridine $(1^{Br}_{-}; 17 \text{ mg})$ 0.065 mmol) in THF (2 mL) at RT. After 12 h, the volatiles were removed under vacuum and the residue was then washed with cold pentane (2 mL, -40 °C). The resulting solid was recrystallized from THF/pentane (1:10 v/v) to yield complex $\mathbf{3}_{=}^{Br}$. Colorless crystals were obtained upon slow evaporation of the solvent at RT (90% yield). Follow-up ³¹P{¹H} NMR spectroscopy of a solution of complex 2^{Br}_ (74 mm) in [D₈]toluene at 24 °C showed the formation of complex $\mathbf{3}_{-}^{Br}$ and the concurrent disappearance of complex $\mathbf{2}_{-}^{Br}$. No intermediates were observed. After \approx 11 h, 75% of the starting material (2_{-}^{Br}) was selectively converted into complex 3_{-}^{Br} . The reaction rate was independent of solvent polarity (toluene vs. acetone) and concentration (see Table 1 for details). Monitoring the transformation of $2^{Br}_{-} \rightarrow 3^{Br}_{-}$ at various temperatures in [D₈]toluene afforded the following first-order rate constants for a concentration of 19 mm: $k_{284K} = 1.0 \times 10^{-5} \text{ s}^{-1}, \quad R^2 = 0.998; \quad k_{287K} = 1.6 \times 10^{-5} \text{ s}^{-1}, \quad R^2 = 0.998; \quad k_{291K} = 3.3 \times 10^{-5} \text{ s}^{-1}, \quad R^2 = 0.997; \quad k_{301K} = 1.2 \times 10^{-4} \text{ s}^{-1}, \quad R^2 = 0.994.$ ¹H NMR (C_6D_6): $\delta = 8.57$ (d, ³J(H,H) = 6.1 Hz, 2H; PyrH), 7.43 (d, ³J(H,H) = 7.8 Hz, 2H; ArH), 7.17 (d, ³J(H,H) = 7.8 Hz, 2H; ArH), 7.06 (d, ³J(H,H) = 16.3 Hz, 1 H; CH=CH), 6.88 (d, ³J(H,H) = 6.1 Hz, 2 H; ArH), 6.78 (d, ³J(H,H) = 16.3 Hz, 1H; CH=CH), 1.53 (m, 12H; PCH_2CH_3), 0.92 ppm (m, 18H; PCH_2CH_3); ${}^{13}C{}^{1}H$ NMR (C_6D_6): $\delta =$ 159.7 (t, ${}^{2}J(P,C) = 6.0 \text{ Hz}$), 150.8, 144.7, 137.4 (t, ${}^{3}J = 4.1 \text{ Hz}$), 133.8, 131.0, 126.3, 123.9, 120.6, 15.3 (t, ¹J(P,C) = 13.2 Hz; PCH₂CH₃), 8.2 ppm (s, PCH₂CH₃); ${}^{31}P{}^{1}H$ NMR (C₆D₆): δ = 12.52 ppm (s, 2 P); MS (ES⁺): m/z calcd for C₂₅H₄₁NPdP₂Br: 603.08; found: 604.54 [M+H]⁺.

Formation of $\mathbf{3}_{=}^{Br}$ from $\mathbf{2}_{=}^{Br}$ in the presence of tetrabutylammonium iodide

A solution of complex 2_{\pm}^{Br} (5.0 mg, 0.0083 mmol) and tetrabutylammonium iodide (3.1 mg, 0.0084 mmol) in [D₈]toluene (0.7 mL) was stirred at 20 °C for 12 h. ³¹P{¹H} NMR spectroscopy indicated full conversion of the starting material (2_{\pm}^{Br}) into two new complexes 3_{\pm}^{Br} (94%) and 3_{\pm}^{I} (6%). Complexes 3_{\pm}^{Br} and 3_{\pm}^{I} were identified by the addition of authentic samples to the reaction mixture. Reacting complex 3_{\pm}^{Br} (5.0 mg, 0.0083 mmol) in [D₈]toluene (0.7 mL) with tetrabutylammonium iodide (3.1 mg, 0.0084 mmol) also resulted in the formation of complex 3_{\pm}^{I} (4%) after 14 h, as determined by using ³¹P{¹H} NMR spectroscopy.

Formation of 3¹

A [D₈]toluene solution of complex 2_{-}^{I} (19 mM) was monitored by using ³¹P{¹H} NMR spectroscopy at -47 °C to show the quantitative formation of complex 3_{-}^{I} and the concurrent disappearance of complex 2_{-}^{I} ($k_{226K} = 6.1 \times 10^{-5} \text{ s}^{-1}$, $R^2 = 0.997$). Formation of complex 3_{-}^{I} became visible after ≈ 15 min. After ≈ 10 h, 90% conversion of the starting material (2_{-}^{I}) was observed. The volatiles were removed under vacuum after an additional reaction time of 4 h. Washing the residue with cold pentane (1 mL, -40 °C) gave complex 3_{-}^{I} (94%). Performing this reaction at various temperatures afforded the following first-order rate constants: $k_{213K} = 5.9 \times 10^{-6} \text{ s}^{-1}$, $R^2 = 0.994$; $k_{219K} = 1.6 \times 10^{-5} \text{ s}^{-1}$, $R^2 = 0.994$; $k_{226K} = 6.1 \times 10^{-5} \text{ s}^{-1}$, $R^2 = 0.994$; $k_{232K} = 1.9 \times 10^{-4} \text{ s}^{-1}$, $R^2 = 0.997$; $k_{232K} = 3.3 \times 10^{-4} \text{ s}^{-1}$, $R^2 = 0.989$. The reaction rate was independent of solvent polarity (toluene vs. acetone) and concentration (see Table 1 for details).

¹H NMR (C₆D₆): δ = 8.69 (d, ³*J*(H,H) = 6.0 Hz, 2 H; PyrH), 7.48 (d, ³*J*(H,H) = 7.6 Hz, 2 H; PyrH), 7.28 (d, ³*J*(H,H) = 7.3 Hz, 2 H; PyrH), 7.17 (d, ³*J*(H,H) = 16.2 Hz, 2 H; CH=CH), 7.01 (d, ³*J*(H,H) = 6.0 Hz, 2 H; ArH), 6.90 (d, ³*J*(H,H) = 16.2 Hz, 2 H; CH=CH), 1.73 (m, 12 H; PCH₂CH₃), 1.02 ppm (m, 18 H; PCH₂CH₃); ¹³C{¹H} NMR (C₆D₆): δ = 161.4 (t, C_q, ³*J*(P,C) = 9.5 Hz), 144.5 (s, C_q), 137.1, 135.8, 133.5, 128.5, 126.0, 123.9, 120.3, 165.5 (t, ¹*J*(P,C) = 27.0 Hz; PCH₂CH₃), 8.0 ppm (s; PCH₂CH₃); ³¹P{¹H} NMR (C₆D₆): δ = 11.43 ppm (s, 2P); MS (ES⁺): *m/z* calcd for C₂₅H₄₁NPdP₂I: 650.08; found: 649.88 [*M*+H]⁺; elemental analysis calcd (%): C 46.20, H 6.20, N 2.16; found: C 46.28, H 6.41, N 1.86.

Formation of 3^{Br}

A solution of complex 2^{Br}_{-} (18 mg, 0.030 mmol) in THF (0.7 mL) was heated in a sealed screw-cap NMR tube to 40 °C. All volatiles were removed after 12 h under vacuum. Washing the residue with cold pentane (-30° C, 1×0.5 mL) gave pure complex $3_{=}^{Br}$ (90% yield). Subsequently, the residue was dissolved in a mixture of Et₂O (0.5 mL) and hexane (1 mL), which resulted in the formation of Xray quality crystals after 24 h at RT. A solution of complex 2^{Br} (18 mg, 0.030 mmol) in [D₈]toluene (0.7 mL; 43 mм) was loaded in a 5 mm screw-cap NMR tube. The reaction progress was monitored by using ³¹P{¹H} NMR spectroscopy to show the selective formation of complex 3_{-}^{Br} and concurrent disappearance of complex 2_{-}^{Br} at various temperatures. No intermediates were observed. First-order linear fits afforded the following values: $k_{293K} = 2.6 \times 10^{-5} \text{ s}^{-1}$, $R^2 =$ 0.999; $k_{298K} = 4.1 \times 10^{-5} \text{ s}^{-1}$, $R^2 = 0.997$; $k_{303K} = 7.6 \times 10^{-5} \text{ s}^{-1}$, $R^2 = 0.997$; $k_{308K} = 2.1 \times 10^{-4} \text{ s}^{-1}$, $R^2 = 0.999$; $k_{313K} = 2.9 \times 10^{-4} \text{ s}^{-1}$, $R^2 = 0.997$; $k_{313K} = 2.9 \times 10^{-4} \text{ s}^{-1}$, $R^2 = 0.997$; $k_{313K} = 2.9 \times 10^{-4} \text{ s}^{-1}$, $R^2 = 0.997$; $k_{313K} = 2.9 \times 10^{-4} \text{ s}^{-1}$, $R^2 = 0.997$; $k_{313K} = 0.997$; 0.998. The reaction rate was independent of solvent polarity (toluene vs. THF) and concentration (see Table 1 for details). ¹H NMR (C_6D_6) : $\delta = 8.52$ (d, ${}^{3}J(H,H) = 5.9$ Hz, 2H; PyrH), 7.43–7.48 (m, 4H; ArH), 7.17–7.18 (d, ³J(H,H) = 5.9 Hz, 2H; ArH), 1.56–1.63 (m, 12H; PCH₂CH₃), 0.96–1.03 ppm (m, 18H; PCH₂CH₃); ¹³C{¹H} NMR (C₆D₆): $\delta = 161.5$ (t, C_q, ²J(P,C) = 11.1 Hz), 150.4, 137.3 (t, ³J(P,C) = 7.7 Hz), 131.6 (s, C_q), 130.7 (s, C), 125.3 (s), 116.3 (s, C_q), 95.4 (s, C_q ; C=C), 86.5 (s, C_q ; C=C), 15.2 (t, ¹J(P,C) = 26.4 Hz; PCH₂CH₃), 8.2 ppm (s; PCH₂CH₃); 31 P{¹H} NMR ([D₈]toluene): δ = 12.20 ppm (s, 2 P); elemental analysis calcd (%) for $C_{25}H_{38}BrNP_2Pd\colon$ C 49.97, H 6.37, N 2.33; found: C 50.08, H 6.49, N, 2.30; HRMS (FD-TOF): m/z calcd: 601.0695; found: 601.0684.

Solid-state formation of 3^{Br}

A yellow powder of complex $2_{\rm B^{\rm r}}^{\rm B^{\rm r}}$ (54 mg, 0.090 mmol) was heated in the absence of light at 40 °C under N₂. After 16 d, a sample was analyzed by using ¹H and ³¹P{¹H} NMR spectroscopy in [D₈]toluene showing 85% conversion of complex $2_{\rm B^{\rm r}}^{\rm B^{\rm r}}$ to complex $3_{\rm B^{\rm r}}^{\rm B^{\rm r}}$. Quantitative formation of complex $3_{\rm B^{\rm r}}^{\rm B^{\rm r}}$ was observed after 24 d.

Formation of 3¹

A solution of $[Pd(PEt_3)_4]$ (9.0 mg, 0.016 mmol) in $[D_8]$ toluene (0.3 mL) was slowly added to a solution of compound 1^I_{\pm} (4.7 mg, 0.015 mmol) in $[D_8]$ toluene (0.4 mL) at RT. Removal of all volatiles after 14 h under vacuum and subsequent washing of the residue with cold pentane (1 mL, -30 °C) gave complex 3^I_{\pm} (94% yield). A solution of complex 2^I_{\pm} (8.6 mg, 0.013) in $[D_8]$ toluene (0.7 mL, 19 mM) was loaded in a 5 mm screw-cap NMR tube. The reaction progress was monitored by using ${}^{31}P{}^{1}H{}$ NMR spectroscopy to show the selective formation of complex 3^I_{\pm} and concurrent disappearance of complex 2^I_{\pm} at various temperatures. No intermediates were observed. The reaction rate was independent of solvent polarity (toluene vs. acetone) and concentration (see Table 1 for de-

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tails). First-order linear fits afforded the following values: $k_{225K} = 9.4 \times 10^{-6} \text{ s}^{-1}$, $R^2 = 0.998$; $k_{240K} = 1.4 \times 10^{-5} \text{ s}^{-1}$, $R^2 = 0.990$; $k_{230K} = 3.1 \times 10^{-5} \text{ s}^{-1}$, $R^2 = 0.998$; $k_{235K} = 4.9 \times 10^{-5} \text{ s}^{-1}$, $R^2 = 0.998$; $k_{250K} = 8.4 \times 10^{-4} \text{ s}^{-1}$, $R^2 = 0.996$. This transformation ($\mathbf{2}^{I}_{\pm} \rightarrow \mathbf{3}^{I}_{\pm}$) was also monitored at 225 K in [D₈]toluene with a lower concentration of complex $\mathbf{2}^{I}_{\pm}$ (3 mM, $k = 1.1 \times 10^{-5}$, $R^2 = 0.999$). ¹H NMR (C₆D₆): $\delta = 8.31$ (d, ³*J*(H,H) = 4.6 Hz, 2 H; PyrH), 7.2 (m, 4H; ArH), 6.95 (d, ³*J*(H,H) = 5.9 Hz, 2H; ArH), 1.47-1.44 (m, 12 H; PCH₂CH₃), 0.81-0.75 ppm (m, 18H; PCH₂CH₃); ¹³C{¹H} NMR (C₆D₆): $\delta = 162.8$ (t, $C_{q'}$ ²*J*(P,C) = 9.5 Hz), 149.9, 137.0 (t, ³*J*(P,C) = 8.0 Hz), 133.4 (s, C_q), 130.2 (s), 125.0 (s), 115.9 (s, C_q), 94.8 (s, C_q; C≡C), 85.3 (s, C_q; C≡C), 15.8 (t, ¹*J*(P,C) = 27.6 Hz; PCH₂CH₃), 7.5 ppm (s; PCH₂CH₃); ³¹P{¹H</sup> NMR ([D₈]toluene): $\delta = 11.38$ ppm (s, 2P). HRMS (ESI⁺): *m/z* calcd for C₂₅H₃₉NP₂IPd: 648.0648; found: 648.0645 [*M*+H]⁺.

Formation of 6

[Pd(PEt₃)₄] (38 mg, 0.066 mmol) was dissolved in toluene (2 mL) and added dropwise to a solution of (E)-4-styrylpyridine (7; 10 mg, 0.055 mmol) in toluene (3 mL) at RT. All the volatiles were removed in vacuo after 6 h to give a light yellow residue. ¹H NMR spectroscopy revealed the formation of complex 6 (88%) and unreacted ligand 7 (12%). ¹H and ¹³C{¹H} NMR spectra were recorded at 0°C to reduce line broadness. ¹H NMR ([D₆]acetone, 0 $^{\circ}$ C): δ = 8.12 (d, ³J(H,H) = 6.0 Hz, 2 H; PyrH), 7.20 (d, ³J(H,H) = 7.9 Hz, 2 H; ArH), 7.10 (t, ³J(H,H) = 7.6 Hz, 2H; ArH), 7.01 (d, ³J(H,H) = 4.7 Hz, 2H; ArH), 7.01 (t, ${}^{3}J(H,H) = 7.0$ Hz, 1 H; ArH), 4.52 (m, ${}^{3}J(P,H) = 16.8$ Hz, ${}^{3}J(P,H) =$ 6.6 Hz, ³J(H,H)=6.1 Hz, 1H; CH=CH), 4.42 (m, ³J(P,H)=16.8 Hz, ³J(P,H) = 6.5 Hz, ³J(H,H) = 6.0 Hz, 1H; CH=CH), 1.54–1.34 (m, 12H; PCH_2CH_3), 0.88 ppm (m, 18H; PCH_2CH_3); ${}^{13}C{}^{1}H$ NMR ([D₆]acetone, 0°C): $\delta = 154.3$ (dd, C_q, ³J(P,C) = 5.6, ³J(P,C) = 2.6 Hz), 150.2, 146.3 (dd, C_q, ³J(P,C) = 6.1 Hz, ³J(P,C) = 1.3 Hz), 128.9 (s), 126.0 (s), 122.6 (s), 118.5 (s), 60.7 (dd, ²J(P,C) = 25.6 Hz, ²J(P,C) = 3.9 Hz; CH=CH) 59.4 $(dd, {}^{2}J(P,C) = 22.7 \text{ Hz}, {}^{2}J(P,C) = 5.1 \text{ Hz}), 18.1 (t, {}^{1}J(P,C) = 12.0 \text{ Hz};$ PCH_2CH_3), 8.2 ppm (d, ²J(P,C) = 3.0 Hz; PCH_2CH_3); ³¹P{¹H} NMR ([D₈]toluene): AB system $\delta_A = 17.30$ ppm (1 P, ²J(P,P) = 18.0 Hz), $\delta_B =$ 15.42 ppm (1 P, ${}^{2}J(P,P) = 18.1$ Hz).

Competition experiments for $2_{=}^{Br}$ with 1-bromo-4-(trifluoro-methyl)benzene (4Br)

A cold solution of complex $\mathbf{2}_{=}^{Br}$ (3.6 mg, 0.0060 mmol) in $[D_{a}]$ toluene (0.3 mL) was mixed with a cold solution of 1-bromo-4-(trifluoromethyl)benzene ($\mathbf{4}^{Br}$; 0.8 mg, 0.004 mmol) in $[D_{a}]$ toluene (0.4 mL) at -60 °C. The reaction mixture was kept at this temperature for 15 min and then allowed to reach RT. $^{19}F_{1}^{(1)}H_{1}^{(1)}$ and $^{31}P_{1}^{(1)}H_{1}^{(1)}$ MMR analysis after ≈ 10 h stirring at RT revealed the quantitative transformation of complex $\mathbf{2}_{=}^{Br}$ into complexes $\mathbf{3}_{=}^{Br}$ (84%) and $\mathbf{5}^{Br}$ (16%), respectively. These products were identified by the addition of authentic samples to the product solution. Complex $\mathbf{3}_{=}^{Br}$ was the only observable product when this reaction was performed with the addition of PEt₃ (12 equiv; 8.5 mg, 0.072 mmol). The PEt₃ was first mixed with a solution containing compound $\mathbf{4}^{Br}$.

Competition experiments of 2^{Br}_{-} with bromobenzene

A cold solution of complex 2_{\pm}^{Br} (4.0 mg, 0.0066 mmol) in $[D_{8}]$ toluene (0.3 mL) was mixed with a cold solution of bromobenzene (0.6 mg, 0.004 mmol) in $[D_{8}]$ toluene (0.4 mL) at $-60\,^{\circ}$ C. The reaction mixture was kept at this temperature for 15 min and then allowed to reach RT. $^{31}P\{^{1}H\}$ NMR analysis after \approx 10 h revealed the quantitative formation of complex 3_{\pm}^{Br} .

Competition experiments of $2^{|}_{=}$ with 1-iodo-4-(trifluoromethyl)benzene (4l)

A cold solution of complex 2_{\perp}^{I} (3.6 mg, 0.0055 mmol) in the presence of PEt₃ (2 equiv) in [D₈]toluene (0.3 mL) was mixed with a solution of 1-iodo-4-(trifluoromethyl)benzene (4^{I} ; 0.8 mg, 0.003 mmol) in [D₈]toluene (0.4 mL) at -60 °C. The reaction mixture was kept at this temperature for 6 h and then allowed to reach RT. ³¹P{¹H} NMR analysis revealed full conversion of complex 2_{\perp}^{I} into complexes 3_{\perp}^{I} (73%) and 5^{I} (27%). These products were identified by addition of authentic samples to the product solution. Quantitative formation of complex 3_{\perp}^{I} was observed when this reaction was carried out in the presence of PEt₃ (12 equiv, 8 mg, 0.07 mmol).

Competition experiments of 2_{\equiv}^{Br} with 1-bromo-4-(trifluoromethyl)benzene (4Br)

A cold solution of complex 2^{Br}_{\equiv} (3.5 mg, 0.0058 mmol) in $[D_8]$ toluene (0.3 mL) was mixed with a cold solution of 1-bromo-4-(trifluoromethyl)benzene (4^{Br} ; 0.70 mg, 0.0031 mmol) in $[D_8]$ toluene (0.4 mL) at $-60\,^\circ\text{C}$. The reaction mixture was kept at this temperature for 15 min and then allowed to reach RT. $^{31}\text{P}^1\text{H}$ NMR analysis after ≈ 10 h, revealed the quantitative transformation of the starting materials into complex 3^{Br}_{\equiv} (70%) and complex 5^{Br} (30%). These complexes were identified by the addition of authentic samples to the reaction mixture. When this reaction was repeated with the addition of PEt_3 (12 equiv, 8.0 mg, 0.067 mmol), quantitative formation of complex 3^{Br}_{\equiv} was observed by using $^{31}\text{P}^1\text{H}$ NMR spectroscopy.

Competition experiments of $2^{|}_{\equiv}$ with 1-iodo-4-(trifluoromethyl)benzene (4l)

A cold solution of complex 2_{\perp}^{I} (3.6 mg, 0.0056 mmol) in the presence of PEt₃ (2 equiv) in [D₈]toluene (0.3 mL) was mixed with a cold solution of 1-iodo-4-(trifluoromethyl)benzene (4^I; 0.8 mg, 0.003 mmol) in [D₈]toluene (0.4 mL) at -60 °C. The reaction mixture was kept at this temperature for 6 h and then allowed to reach RT. ³¹P{¹H} NMR spectroscopy revealed full conversion of complex 2_{\perp}^{I} and the formation of complexes 3_{\perp}^{I} (66%) and 5^{I} (34%). On performing this reaction with the addition of PEt₃ (12 equiv, 8 mg, 0.07 mmol), formation of complexes 3_{\perp}^{I} (97%) and 5^{I} (3%) was observable by ¹H, ¹⁹F{¹H}, and ³¹P{¹H} NMR spectroscopy. These complexes were identified by the addition of authentic samples to the reaction mixture.

Competition experiments of 6 with 1-bromo-4-(trifluoromethyl)benzene (4^{Br})

A solution of complex **6** (4.5 mg, 0.0086 mmol) and PEt₃ (2 equiv) of in [D₈]toluene (0.3 mL) was mixed with a solution of 1-bromo-4-(trifluoromethyl)benzene (4^{Br} ; 2.0 mg, 0.0088 mmol) in [D₈]toluene (0.4 mL) at -30 °C. ¹H and ³¹P{¹H} NMR spectroscopy showed the formation of compound **7** and complex **5**^{Br} in 95% yield.

X-ray crystallographic analysis

X-ray analysis of $2_{=}^{Br}$

Crystal data: $C_{25}H_{38}$ NBrP₂Pd; colorless; prisms; $0.4 \times 0.3 \times 0.2$ mm⁻³; triclinic; $P\bar{1}$; a=14.1542(2), b=14.5498(2), c=15.0008(1) Å; a=67.7701(7), $\beta=88.5428(6)$, $\gamma=72.7628(6)^{\circ}$; T=120(2) K; V=2718.06(6) Å³; Z=4; $M_r=600.81$; $\mu=2.283$ mm⁻¹; $\rho_{calcd}=1.47$ mg m⁻³.

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Data collection and processing: Nonius Kappa CCD diffractometer; $Mo_{K\alpha}$ ($\lambda = 0.71073$ Å); graphite monochromator; $-18 \le h \le 18$, $-17 \le k \le 18$, $0 \le l \le 19$; frame scan width $= 1.0^{\circ}$; scan speed 1.0° per 20 sec; typical peak mosaicity 0.52° ; 52 926 reflections collected, 12 397 independent reflections ($R_{int} = 0.036$); $2\theta_{max} = 54.94^{\circ}$. The data were processed with Denzo-Scalepack.

Solution and refinement: The structure was solved by using direct methods with SHELXS-97.^[33] The full-matrix least-squares refinement is based on F^2 with SHELXL-13,^[33] 541 parameters with 0 restraints, final $R_1 = 0.0259$ (based on F^2) for data with $I > 2\sigma(I)$ and $R_1 = 0.0356$ on 12395 reflections, goodness-of-fit on $F^2 = 1.088$, largest electron density peak = 0.721 eÅ⁻³ and largest hole -0.600 eÅ⁻³.

X-ray analysis of 3_{-}^{Br}

Crystal data: $C_{25}H_{40}$ NBrP₂Pd; colorless; prisms; 0.1×0.1×0.1 mm⁻³; orthorhombic; *Pna*2(1); *a*=15.962(3), *b*=14.889(3), *c*=11.611(2) Å; *T*=120(2) K; *V*=2759.4(9) Å³; *Z*=4; *M*_r=602.83; ρ_{calcd} = 1.45 mg m⁻³; μ =2.249 mm⁻¹.

Data collection and processing: Nonius KappaCCD diffractometer; Mo_{Kα} ($\lambda = 0.71073$ Å); graphite monochromator; $0 \le h \le 19$, $0 \le k \le 17$, $0 \le l \le 13$; 23 256 reflections collected, 2641 independent reflections ($R_{int} = 0.0325$); $2\theta_{max} = 55.10^{\circ}$. The data were processed with Denzo-Scalepack.

Solution and refinement: The structure was solved by using direct methods with SHELXT-13.^[33] The full matrix least-squares refinement is based on F^2 with SHELXL-13,^[33] 254 parameters with 3 restraints, final $R_1 = 0.0457$ (based on F^2) for data with $I > 2\sigma(I)$ and $R_1 = 0.0557$ on 3308 reflections, goodness-of-fit on $F^2 = 1.068$, largest electron density peak = 1.681 e Å⁻³ and largest hole = -1.083 e Å⁻³.

X-ray analysis of $3_{=}^{Br}$

Crystal data: $C_{25}H_{38}$ NBrP₂Pd; colorless prisms; $0.6 \times 0.2 \times 0.2 \text{ mm}^3$; monoclinic, *P*21/*c*; *a*=15.713(3), *b*=28.456(6), *c*=13.812(3) Å; β =115.80(3)°; *T*=120(2) K; *V*=5560(2) Å^3; *Z*=8; *M*_r=600.81; ρ_{calcd} = 1.435 mg m⁻³; μ =2.232 mm⁻¹.

Data collection and processing: Nonius KappaCCD diffractometer; Mo_{Kα} ($\lambda = 0.71073$ Å); graphite monochromator; $-20 \le h \le 18$, $0 \le k \le 36$, $0 \le l \le 17$; frame scan width $= 0.7^{\circ}$; scan speed 1.0° per 98 s; typical peak mosaicity 0.69°; 40653 reflections collected, 12606 independent reflections ($R_{int} = 0.065$); $2\theta_{max} = 54.96^{\circ}$. The data were processed with Denzo-Scalepack.

Solution and refinement: The structure was solved by using direct methods with SHELXT-13.^[33] The full matrix least-squares refinement is based on F^2 with SHELXL-13,^[33] 553 parameters with 0 restraints, final $R_1 = 0.0465$ (based on F^2) for data with $I > 2\sigma(I)$ and $R_1 = 0.0772$ on 12606 reflections, goodness-of-fit on $F^2 = 1.029$, largest electron density peak=0.877 eÅ⁻³ and largest hole= -0.739 eÅ⁻³.

CCDC 1413587–1413589 contain the supplementary crystallographic data for this paper. These data are provided free of charge by The Cambridge Crystallographic Data Centre.

Computational details

All calculations used either Gaussian 09, Revision D.01^[34] or ORCA 3.0.2.^[35] Geometry optimizations and DFT calculations were done with the former, whereas single-point-energy double-hybrid DFT and ab initio (see below) calculations were done with the latter. Geometries were optimized with the local version of Truh-

lar's Minnesota-06 suite of functionals^[36] (i.e., M06-L),^[37] with an empirical dispersion correction added,^[38] specifically the third version of Grimme's dispersion,^[38b] this combination is denoted as M06-L_{n3}.

When using a GGA functional, density fitting basis sets, specifically the fitting sets generated by using the automatic generation algorithm implemented in Gaussian 09, were used in order to speed up the calculations.^[39] In the thermochemical analyses, the frequencies were scaled by the 0.9958 factor recommended by Kesharwani et al.^[26] and the different experimental temperatures were used as applicable. Energies were calculated by using domain-based local pair natural orbital coupled cluster with single and double excitations and a guasi-perturbative triples treatment (DLPNO-CCSD(T)) calculations^[40] with the resolution of identity chain of spheres exchange (RIJCOSX) approximation^[41] used to increase the speed of the calculations. Orbitals were localized according to the Pipek-Mezey method.^[42] The reliability of the DLPNO approximations has recently been examined.^[43] For geometry optimizations, the def2-SVP basis set^[44] was used, which includes a relativistic effective core potential (RECP) on palladium, bromine, and iodine. The same basis set and the def2-TZVP counterpart were used for all DFT calculations. Ab initio calculations used the cc-pVDZ-PP and cc-pVTZ-PP basis set-RECP combinations, which combine Dunning's ccpVnZ basis sets^[45] with Peterson's basis set-RECP combinations for the heavier elements.^[46] Basis set superposition error (BSSE) corrections were estimated by using the counterpoise correction (CP) method suggested by Boys and Bernardi.^[47] The correction is equal to Equation 1:

$$\Delta E_{\rm CP} = E_{\rm AB}^{\rm AB}(\rm AB) - E_{\rm A}^{\rm A}(\rm A) - E_{\rm B}^{\rm B}(\rm B) - [E_{\rm A}^{\rm AB}(\rm AB) - E_{\rm A}^{\rm AB}(\rm AB) - E_{\rm B}^{\rm AB}(\rm B)]$$

$$(1)$$

in which $E_{\rm Y}^{\rm X}({\rm Z})$ is the energy of fragment X calculated at the optimized geometry of Y with the basis set of fragment Z. This was done for M06 by using the "counterpoise" keyword in Gaussian 09 and according to the example in the ORCA users' manual for the other cases.

Bulk solvent effects were approximated by single-point energy calculations by using a polarizable continuum model (PCM),^[48] specifically the integral equation formalism model $(\mathsf{IEF}\text{-}\mathsf{PCM})^{^{[48a,b,49]}}$ with toluene as the solvent, as in the experiments. Specifically, Truhlar's empirically parameterized version solvation model density (SMD) was used.^[50] Two methods for correcting for solvation were used for the CCSD(T) calculations. The first is to correct the gas-phase energies with the difference between the solution SMD-M06 and gas-phase M06 energies using either the def2-SVP or def2-TZVP basis set; this is denoted as $\Delta E_{MO6/SVP}^{SMD}$ or $\Delta E_{MO6/TZVP < brtr>SMD'}$ respectively. The second is to apply the post-Hartree-Fock (HF) correlation calculation to the SMD-HF orbitals; this is denoted as SMD-CCSD(T). The difference in the energies between the three solvation options is insignificant. The $\Delta E_{MO6/TZVP}^{SMD}$ results are presented in the paper whereas the SMD-CCSD(T) results, along with other tested considered levels of theory, are presented in the Supporting Information in Table S7; these include the M06 functional (the hybrid version of M06L used for geometry optimizations),^[51] the DSD-PBEB95^[52] double-hybrid functional^[53] and second-order Møller-Plesset (MP2)^[54] (obtained as a byproduct of the CCSD(T) calculation).

In all DFT calculations run with Gaussian 09, an ultrafine (i.e., a pruned (99,590)) grid was used, which is especially critical for the M06 suite of functionals.^[55] For interpretative purposes, Mayer^[56]

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and Wiberg^[57] BOs and NBO analyses^[58] were used; the NBO analyses were done by using NBO6.^[59]

Following convention, free energies are reported at standard state, that is, 1 atm and 298.15 K. By redoing the thermochemical analysis within Gaussian 09 at other temperatures, one can obtain the free energies at different temperatures. The corrections for varying concentrations can also be obtained,^[60] details are provided in the Supporting Information (Table S1).

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