Investigating the Dearomative Rearrangement of Biaryl Phosphine-Ligated Pd(II) Complexes

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INVESTIGATING THE DEAROMATIVE REARRANGEMENT OF BIARYL PHOSPHINE-LIGATED PD(II) COMPLEXES

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Abstract
A series of monoligated L•Pd\(^{\text{II}}\)(Ar)X complexes (L = dialkyl biarylphosphine) have been prepared and studied in an effort to better understand an unusual dearomative rearrangement previously documented in these systems. Experimental and theoretical evidence suggest a concerted process involving the unprecedented Pd\(^{\text{II}}\)-mediated insertion of an aryl group into an unactivated arene.

INTRODUCTION
Dialkyl biaryl phosphine ligands have seen application in a variety of Pd-catalyzed cross-coupling reactions, including those forming C—C,\(^1\) C—N,\(^2\) C—O,\(^3\) C—CF\(_3\),\(^4\) and C—X (X = F, Cl, Br),\(^5\) bonds. Catalysts based on derivatives of 2-(di-\(\text{-}t\)-butylphosphino)biphenyl (JohnPhos, \(^1\)),\(^6\) such as SPhos (\(^2\)),\(^1\)a,d, 7 RuPhos (\(^3\)),\(^2\) XPhos (\(^4\)),\(^1\)b, 8 \(\alpha\)BuXPhos (\(^5\)),\(^1\)c–f, 9 Me\(_4\)\(\alpha\)BuXPhos (\(^6\)),\(^3\)c, 9f, 10 BrettPhos (\(^7\)),\(^2\), 4, 11 \(\alpha\)BuBrettPhos (\(^8\)),\(^5\), 12 AdBrettPhos (\(^9\)),\(^13\) and RockPhos (\(^10\)),\(^3\)b have demonstrated particular proficiency in these reactions (Figure 1). Biaryl phosphine ligands have also proven effective in the preparation of a number of transition metal complexes, the structures of which have revealed that the non-phosphine containing (lower) aromatic ring often serves as an additional binding site to the metal center.\(^14\)

While studying the Pd-catalyzed conversion of aryl triflates to aryl fluorides,\(^5\)_a we discovered an unexpected rearrangement of the oxidative addition complex \(^{11a}\) that established an equilibrium (\(K_{\text{eq}} = 5.71 \pm 0.10\), CD\(_2\)Cl\(_2\)) between \(^{11a}\) and dearomatized \(^{11b}\) (Figure 2) at room temperature.\(^15\) The analogous complex \(^{12a}\) derived from \(^{10}\), which differs only in the substitution of a methyl group for a methoxy group, was also found to undergo rearrangement to \(^{12b}\), albeit to a much lesser degree (\(K_{\text{eq}} = 0.08\), CD\(_2\)Cl\(_2\)). Treatment of the \(^{11a}/^{11b}\) equilibrium mixture with DBU in the presence of 4-\(n\)-BuPhBr generated \(^{13}\), the oxidative addition complex of 3'-arylated \(\alpha\)BuBrettPhos, presumably via a L•Pd(0) intermediate (Figure 3).

The arene-binding interaction observed in complexes of biaryl phosphine ligands could, in principle, facilitate dearomatization if enough weakening of the aromatic character of the lower ring occurred. Accordingly, other dearomatized biaryl phosphine-ligated transition
metal complexes have been recently reported. Prior to our work, Doyle reported a
dearomatized 7-ligated Ni(II) complex (14),\textsuperscript{16} and recently Allgeier and Shaw reported the
decomposition of a tBuXPhos complex to give 15, purportedly by a carbene insertion
mechanism originating from dichloromethane (Figure 4).\textsuperscript{17} In both of these cases,
dearomatization occurs at the 4' position of the lower arene (see Figure 4), whereas 11b
shows a different connectivity that allows for the loss of HBr and rearomatization to occur.
Taken together, these reports suggest that the lower ring of biaryl phosphine ligands may not
be innocent in the reactivity and decomposition pathways of catalytic intermediates.

Reactions wherein a transition metal-bound arene undergoes nucleophilic attack are well-
established,\textsuperscript{18} as are a number of dearomatization reactions using Pd and Pt catalysts.\textsuperscript{19}
However, the reversible rearrangement of 11a/11b, which formally represents an aryl
migratory insertion into an aromatic ring, is quite unusual. Concerted aryl migratory
insertion processes from Pd(II) have been proposed as a potential pathway in a large number
of C-H arylation reactions,\textsuperscript{20} but little is known experimentally about the viability of this
process, and the direct observation of the product of the insertion of an aryl group into an
aromatic ring from Pd(II) had never, to our knowledge, been reported prior to our work.
Likewise, the reverse of this process would represent a rare example of β-aryl elimination
from an isolated Pd(II) complex.\textsuperscript{21, 22} Due to the increasing number of reports concerning
dearomatization reactions of biaryl phosphine-ligated complexes, the importance of these
ligands in difficult cross-coupling reactions, and the possible relevance of the mechanism of
this process to those of C-H arylation reactions,\textsuperscript{20} we set out to investigate the mechanistic
features of this rearrangement both experimentally and computationally.

Several possible mechanisms for the rearrangement of 11a to 11b are shown in Scheme 1.
Numerous mechanistic studies of aryl migratory insertions into alkenes using bidentante
ligands or small monodentate ligands have been conducted.\textsuperscript{23} Most relevant to this study,
Brown found that intramolecular migratory insertions of electron-rich Pd(II) complexes are
incredibly facile, and with monodentate phosphine ligands the insertion most likely proceeds
directly from the L•Pd(aryl)X(alkene) species.\textsuperscript{24} In the solid state structure of 11a, the aryl
group and lower ring of the ligand are trans, but a concerted insertion requires the
π system and migrating groups to be cis. Therefore, isomerization (possibly by pseudo-rotation of a
tricoordinate 14-electron Pd-species) to cis 11a© must occur before a concerted 1,4-
migratory insertion into the arene (Pathway I) or a concerted 1,2-migratory insertion to form
16 followed by a 1,3-allylic shift (Pathway II). Several cationic mechanisms (Pathways III-
IV), wherein halide disassociation to 17 precedes 1,2- or 1,4-migratory insertion (III) as
from 11a©, or Friedel-Crafts-type electrophilic palladation to give 17© followed by 1,2- or
1,4-aryl migration (IV), could also be envisioned (Scheme 1).\textsuperscript{25} With these mechanistic
possibilities in mind, we investigated the effect of solvent, halide, aryl substituent, and
ligand structure on the rate and extent of rearrangement to determine which pathway is most
likely operative in the dearomatization of 11a.

EXPERIMENTAL STUDIES

1.1 Activation Parameters

The activation parameters for the rearrangement of 11a to 11b were determined by Eyring
analysis (10–42 °C, CD\textsubscript{2}Cl\textsubscript{2}, Supporting Information Figure S2) to be ΔH\textsuperscript{‡} = 22.1 ± 1.3
kcal/mol, ΔS\textsuperscript{‡} = 16 ± 4 cal/K•mol, and ΔG\textsuperscript{‡} (20 °C) = 17.4 ± 1.3 kcal/mol. The positive
entropy of activation suggests that extensive reorganization of the species going to the rate-
determining transition state is not necessary (\textit{vide infra}). These parameters could be
consistent with any of the mechanistic scenarios shown in Scheme 1.
1.2 Solvent Effects

The $^{31}$P NMR spectrum of 11a displays only one resonance, however it is unusually broad, especially when compared to the analogous complex 12a bearing the structurally similar RockPhos ligand (Figure 5). The broad $^{31}$P NMR resonance of 11a is indicative of multiple rapidly equilibrating species being present in solution, consistent with the presence of both 11a and 11a'. However, low temperature (−80 °C) decoalescence and NOESY NMR experiments could not definitively establish the identity of the species present in solution (see Supporting Information).

Solvent effects on the rate and extent of rearrangement of 11a to 11b were also examined (Table 1). The relative rates of isomerization ($k_{f+r}$) and equilibrium ($K_{eq}$) constants were determined in THF-d$_8$, C$_6$D$_6$, dioxane-d$_8$, and CD$_2$Cl$_2$. From these two parameters, the $k_f$ rate constants for the forward rearrangement process could be determined. These findings suggest that solvation has a minor effect on the relative stabilities of 11a and 11b, yet there is no discernible trend between solvent polarity and equilibrium concentration or rate of rearrangement. Because halide dissociation must be rate-determining or precede the rate-determining step in Pathways III and IV, these results are inconsistent with an ion-dissociation pathway, which previous studies suggest should be uniformly accelerated by more coordinating solvents such as THF and dioxane. The observation that the addition of 5 eq. of soluble Br− (Bu$_4$NBr) did not decrease the rate of rearrangement is also consistent with this premise.

1.3 Aryl Substituent Effect

A range of para-substituted aryl bromide oxidative addition complexes based on 8 were synthesized in good isolated yields (Table 2). The kinetic profiles for the rearrangements of these species are shown in Figure 6, and the parameters corresponding to these profiles are shown in Tables 3a and 3b. A Hammett plot of the $K_{eq}$ values in Table 3a was linear, yielding $\rho = -2.56 \pm 0.13$ (Figure 7). Only with substituents that are electron-withdrawing by both resonance and induction (24a, 25a) is the oxidative addition complex lower in energy than its dearomatized isomer. Because the aryl group is bound to a sp$^3$-hybridized carbon in the dearomatized complex, but interacts directly with the Pd center in the corresponding oxidative addition complexes, its identity should be of more consequence to the stability of 11,18±25a than to 11,18±25b; that is, electron-donating substituents must destabilize oxidative addition complexes of 8 relative to their dearomatized counterparts. The solid state structures of 11a, 20a, 22a, and 25a (see Supporting Information for individual structures) provide insight into why this might be (Figure 8). No significant changes in the length of Pd-Br (2.46–2.47 Å) and Pd-P (2.34–2.35 Å) bond lengths were found among the four complexes, and the expected changes in the Ar-Pd-Br bond angles based on the relative ease of reductive elimination were observed. The Pd-C1' (ipso carbon of the lower ring) distance grows longer as the aryl group becomes more electron-rich (see Figure 9), due to the stronger trans influence of electron-rich aryl ligands. Likewise, the Pd-Ar bond lengthens slightly as the aryl substituent becomes more electron-rich, likely due to the weaker $\pi$-accepting ability of more electron-rich aryl substituents. Therefore, increasing the electron-donating ability of the aryl group weakens stabilization of the oxidative addition complex by the lower ring, making oxidative addition complexes with electron-rich aryl substituents less stable than those with electron-withdrawing aryl substituents. This effect could also facilitate the proposed cis/trans isomerization step in Pathways I-II if lower-ring disassociation is necessary for this process to occur.

Although the Hammett plot of the rates of isomerization ($k_{f+r}$) in Table 3b was non-linear (not shown), the Hammett plot of the $k_f$ values was linear, yielding $\rho = -1.58 \pm 0.16$ (Figure 9), confirming that electron-donating groups on the aryl substituent increase the rate of
dearomatization. This is likely due in part to the aforementioned ground state weakening of the Pd-C_Ar and Pd-C_1' bonds as the aryl substituent becomes more electron-rich, as these bonds must be cleaved for the insertion to occur. In addition, in the transition state of a concerted insertion C_Ar migrates from Pd to C2', which is more electronegative than Pd, and thus C_Ar would be expected to become more electron-deficient as the insertion occurs. Electron-donating groups on the aryl substituent would mitigate this loss in electron density and thus facilitate the proposed concerted rearrangement. Therefore, the Hammett plot in Figure 9 is also consistent with a concerted insertion process.

1.4 Halide Effect

We next investigated the influence of the halide ligand on the rearrangement of tBuBrettPhos oxidative addition complexes. The chloride (26a), iodide (27a), and triflate (28a) analogues of 11a were prepared in the same manner as 11a (Table 4). Pd(II) complexes bearing Cl, Br, and I ligands all feature 31P NMR resonances in the 665–70 ppm range (CD2Cl2); however, triflate complex 28a possesses a much further downfield 31P resonance (δ 111 ppm, C6D6), suggesting the triflate group is dissociated in solution. X-ray crystallographic analysis revealed that the phenyl analogue of 28a is formally cationic at Pd in the solid state, with additional stabilization provided by the lower ring of the ligand (Figure 10). Not surprisingly, 28a was found to be susceptible to solvent coordination, so its rearrangement to 28b was studied in C6D6 instead of THF-d8. Iodide complex 27a proved unstable in both THF-d8 and C6D6, with free ligand slowly growing in (with generation of Pd black), in addition to a species with 31P NMR (121 MHz, C6D6) shift at approximately δ 120 ppm. Thus, we hesitate to assign definite kinetic or thermodynamic parameters to its rearrangement to 27b. The observed trend for equilibrium constants is Br > Cl >> OTf (Table 4), which follows the trend observed in Table 3a, as Cl is inductively more electron-withdrawing than Br, and the OTf complex 28a is formally cationic. Although 27a eventually decomposed in solution, we observed minimal formation of 27b (~16%) during the first hour in THF-d8, consistent with a rate trend of Cl > Br > I.

Exchanging the bromide ligand in 11a for a chloride ligand in 26a accelerates the rate of rearrangement (as with an electron-donating aryl substituent, Figure 9) but reduces the extent of rearrangement (as with an electron-withdrawing aryl substituent, Figure 7). Although Cl is inductively more electron-withdrawing than Br, it is a stronger π-donor to the Pd center; thus, the interplay of these two effects likely causes the observed difference in reactivity between 11a and 26a. However, at this time we cannot determine what role the halide ligand has in the rearrangement process.

1.5.1 Ligand Structure Effects: Groups on Phosphorus

The alkyl groups bound to phosphorus in biaryl phosphine ligands play a key role in determining the catalytic activity of their Pd complexes; bulkier ligands, i.e. those bearing t-butyl and adamantyl groups, are typically used in cross-coupling reactions that have difficult reductive elimination steps. Thus, we decided to investigate the behavior of complexes of ligands analogous to 8 with different substituents on the phosphorus atom. Several oxidative addition complexes of the dicyclohexyl ligand BrettPhos (7) have been previously reported. In none of these reports was any rearrangement of the corresponding oxidative addition complexes observed, although complexes derived from BrettPhos were found to exist as either C- or O-bound isomers is solution (these isomers are not observed in complexes of di-t-butyl ligands). Considering Doyle’s recent observation of 15,16 we decided to monitor the solution stability of 7+Pd(4-η-BuPh)Br (29a) by 1H NMR (Table 5). Even after 10 days in solution no rearrangement to 29b was observed. Oxidative addition complexes of other dicyclohexyl based biaryl phosphate ligands, including 2,1b 3,30 and 4,1b have also been prepared or detected in situ with no report of anomalous behavior. To
further test the effect of the substituents on phosphorus, 30a was synthesized using the recently reported di-adamantyl analogue of 8.\textsuperscript{13} In solution, this complex rearranges to 30b with kinetic and thermodynamic parameters similar to those observed for the conversion of 11a to 11b (Table 5). This is not surprising, given the similar size of the t-butyl and adamantyl groups near the Pd center. Thus, the relief of unfavorable steric interactions between the aryl group and t-butyl (or adamantyl) groups is likely a driving force for rearrangement, as it is for reductive elimination. This finding is consistent with the positive $\Delta S^\ddagger$ of the rearrangement process (\textit{vide supra}), as the rearranged species should possess more rotational degrees of freedom for both the t-butyl and aryl substituents than in the corresponding oxidative addition complex.

1.5.2 Ligand Structure Effects: Substituents on the Biaryl Backbone

Due to the radically different behavior of complexes of tBuBrettPhos (8) and RockPhos (10), the effect of substituents on the phosphine-containing ring of the biaryl backbone was investigated. Because a change from a methoxy group in the 6-position of 11a to a methyl group in 12a greatly decreased the $K_{eq}$ and rate of rearrangement (~5% rearrangement after 6 hours), we hypothesized that bulkier substituents in the in the 6-position might retard rearrangement. Similarly, the fact that 5•Pd(4-\textit{n}-BuPh)Br (31a) was found to rearrange to 31b to only a small degree (Table 6) suggested that the substituent in the 3-position found in 11a but not in 31a might promote rearrangement. Thus, a variety of complexes were synthesized in order to test the effect of substituents in the 3- and 6-positions on the rate of rearrangement and the equilibrium ratio of complexes (Table 6). When attempting to prepare 32a, the oxidative addition complex of a BrettPhos-type ligand with no substituent in the 6-position,\textsuperscript{3b} we observed that the product that precipitated from the reaction mixture was already an equilibrium mixture heavily favoring rearranged complex 32b (Table 6). To probe whether the enhancement of rearrangement by a substituent in the 3-position was due to either steric or electronic effects, we attempted to synthesize 33a (R = Me).\textsuperscript{32} As with 32a, only an equilibrium mixture favoring 33b could be obtained (Table 6). An equilibrium constant ($K_{eq}$) of 15 was determined for this complex and is the largest value seen for any ligand in the series of oxidative addition complexes where Ar = 4-\textit{n}-BuPh. Finally, 34a, which has a methyl group in the 6-position but no substituent in the 3-position of the ligand, was prepared. In accordance with previous findings, only trace amounts (~1%) of 34b could be detected in solution by $^1$H NMR.

Overall, these results confirm that substituents in the 3-position promote both the rate and extent of dearomatization, whereas substituents in the 6-position inhibit the process. Based on the equilibrium constants of complexes 32a/32b and 33a/33b, the promotion of rearrangement by substituents at the 3-position appears to be a steric effect that most likely arises from this substituent "pushing" the t-butyl groups closer to the Pd center, an effect also thought to promote reductive elimination. The solid state structures of 11a, 12a, and 11b provide an explanation for the effect of substituents in the 6-position of the phosphine-containing ring on the extent of rearrangement at equilibrium. Viewing 11a and 12a along the axis that contains the biaryl bond and bisects both the lower and phosphine-containing rings (as shown in Figure 11), the lower and phosphine-containing rings are almost perfectly perpendicular to one another, as would be expected. Due to the near perpendicularity of the two rings, the distance between the ortho-isopropyl groups and the substituent at the 6-position (a methoxy group in 11a, a methyl group in 12a) is similar, with an observed average distance of 3.55 Å in 11a and 3.77 Å in 12a. The longer observed distance in 12a than in 11a reflects the longer bond length of the C-C bond in 12a (1.51(4) Å) compared to the C-O bond in 11a (1.37(6) Å).
However, viewing the solid state structure of 11b in the same manner reveals that the lower ring is significantly tilted relative to the phosphine-containing ring following de-aromatization (Figure 12). This tilting effectively positions the isopropyl group adjacent to the Pd-center farther from the methoxy group at the 6-position but, more importantly, positions the other isopropyl group (highlighted in yellow in Figure 12) roughly 0.5 Å closer to the methoxy group than it was in 11a. The decrease in distance between these two substituents upon de-aromatization should result in a stronger steric interaction between them. In 12b the substituent at the 6-position is a significantly larger than that in 11a, suggesting that the increase in steric repulsion following de-aromatization should be even more dramatic for 12b than for 11b and could be enough to significantly destabilize the de-aromatized complex. This ground state effect is the most likely explanation for why 12a de-aromatizes to such a lesser extent than 11a. The effect of the substituent at the 6-position on transition states, and thus its effect on the relative rates of rearrangement for the two complexes, is more difficult to determine.

### 1.5.3 Ligand Structure Effect: Further Studies of Complexes of 5 and 10

In order to determine if the trends we observed for complexes of 8 were generalizable to other commonly employed di-t-butyl biaryl phosphine ligands, we further examined the reactivity of complexes bearing tBuXPhos (5) and RockPhos (10) as ligands. Thus, additional complexes of 5 (35a–38a) and 10 (38–40a) were synthesized to compare with the corresponding complexes of 8 (Table 7). Crystal structures of these complexes were obtained and show similar structural features and trends to those of 8, including the lengthening of the Pd- ipso interaction as the arene becomes more electron-rich (see Supporting Information for individual X-ray structures). The aryl substituent equilibrium constant trend of NMe$_2$ > n-Bu > H > CN demonstrated for complexes of 8 in Table 3 was also observed for complexes of 5 and 10, with no detectable rearrangement of 37a and 40a observed even after even after several days in solution (Table 7). In addition, the observed trend in extent of rearrangement for varying the phosphine ligand in the 4-n-BuPh complex series, namely 8 > 5 > 10 (Table 6), also held true for the 4-NMe$_2$ and Ph series. Thus, the results and analysis we described for complexes of 8 likely hold true for complexes of 5 and 10 as well.

Taken together, these results show that the rearrangement of dialkyl biaryl phosphine-ligated Pd(II) complexes is heavily dependent on the steric parameters of both the phosphine-containing ring of the ligand and well as the alkyl groups on the phosphorus atom. It is important to note that all studied complexes bearing di-t-butyl biaryl phosphine ligands show at least some ability to rearrange in solution except for the arylated tBuBrettPhos complex 13. Interestingly, the main structural difference between 11a and 13 is a distortion from ideal square-planar geometry observed in 11a (and in all solid state structures that have been obtained for oxidative addition complexes of 5, 8, and 10) that is not observed in the solid state structure of 13. When 11a is viewed down the biaryl axis (as shown in Figure 11), it becomes clear that the angle between the ipso carbon and the aryl substituent (ipso-Pd-Ar) is not 180° as it would be in an ideal square planar complex; instead, this angle is approximately 158° due to tilting of the aryl substituent towards one side of the lower ring of the ligand. In addition, the P-Pd-Br angle is distorted approximately 13° from linearity. This "tilting" could indicate a ground-state predilection towards de-aromatization in these complexes. However, when 13 is viewed in the same manner (as shown in Figure 13), no significant distortion of the ipso-Pd-Ar angle (178° in 13) from linearity is observed, and the P-Pd-Br is significantly closer to linearity (176°) than in 11a. Thus, the 3'-aryl substituent imposes a stronger square planar geometry at the metal center, which seems to prevent a second de-aromatization event from occurring.
**COMPUTATIONAL STUDIES**

2.1 Calibration of Structures and Energies for 11a and 11b

In order to shed more light on the rearrangement process, especially with regard to the mechanism of aryl insertion, we turned to density functional theory (DFT). All calculations were performed using the Q-Chem quantum chemistry package. Density functionals and basis sets were evaluated based on their ability to reproduce the experimentally determined relative energies of 11a and 11b, as well as the structural features present in both solid state structures. The basis set LANL2DZ was used for all calculations. The Perdew-Becke-Ernzerhof (PBE) functional resulted in the most accurate energy difference between 11a and 11b (ΔE = −0.43 kcal/mol); most other tested density functionals gave ΔE values that were too large (see Supporting Information). In addition, the optimized geometry of 11a using PBE/LANL2DZ was found to closely resemble the obtained crystal structure. For example, whereas other functionals overestimated the length of the ipso interaction, indicating an incorrect treatment of this unusual bonding mode, PBE/LANL2DZ reproduced this distance fairly accurately (Calc. 2.58 Å, Exp. 2.53 Å). The optimized structures of 11a and 11b using PBE/LANL2DZ are shown in Figure 14; this basis set and density functional combination were chosen for all subsequent computational work. The choice of PBE/LANL2DZ was further validated by the ability of this basis set/functional combination to reproduce the experimental trend for the relative energies of the series of aryl-substituted oxidative addition complexes of 8 shown in Table 3a (Table 8). Notably, the DFT calculations systematically underestimate how much of the rearranged isomer should be present at equilibrium. A Hammett plot of the calculated equilibrium constants (Figure 15) shows a worse linear fit than the experimental data (due primarily to the outlier CHO data point), but yielded ρ = −2.78 ± 0.36, which agrees well with the experimentally determined ρ value of −2.56 ± 0.13 (Figure 7). Thus, the PBE/LANL2DZ combination adequately reproduces the structural trends observed for complexes of 8.

2.2 Molecular Orbital Description of Rearrangement.

The optimized geometry and solid state structure of 11b both possess a trigonal planar geometry around the Pd(II) center, distinct from the more commonly observed square planar geometry assumed by 11a. By comparing the relative ordering of the 4d orbitals in the Kohn-Sham molecular orbitals (MOs) obtained from DFT calculations for 11a and 11b (see Computational Supporting Information for all calculated MOs), we can establish the extent of crystal field splitting for these two complexes. Thus, the relative 4d orbital ordering of \( xz < xy < yz < z^2 < x^2 - y^2 \) for 11a and \( xz < xy < yz < z^2 < x^2 - y^2 \) for 11b dictates that both complexes reside in the regime of large crystal field splitting (See Computational Supporting Information for more detailed calculations). This is important because in this regime a trigonal planar geometry around a Pd(II) center can be close in energy to a square planar geometry. A strong ligand field for these complexes would also explain the weak effect of solvent on the rate and extent of rearrangement observed in Table 1, as the identity of the solvent should not significantly change the electronic environment of the metal center.

We further examined those Kohn-Sham MOs for 11a and 11b that show any orbital interaction between the 4d orbitals on the metal center and the lower ring of the ligand to investigate the ipso interaction in 11a as well as the fate of this interaction after rearrangement to 11b. Overlap between one lobe of Pd 4d\(yz\) and the \(\pi\)-system of the lower ring (σ1, Figure 16) at C1’ suggests that the ipso interaction is analogous to a strong σ-bond between the lower ring and the Pd center. Interestingly, in this MO there is also a small amount of in-phase orbital density on adjacent C2’, which is where the Pd center ultimately forms a σ-bond during the dearomatization process. Thus, the dearomatization likely occurs...
by increasing this bonding interaction between the Pd-center and C2' at the expense of the π-system of the lower ring.

Three relevant occupied MOs that depict the unusual bonding orientation in 11b were also found (Figure 16); their relative energies are π*1 > n1 > σ2. In σ2, the 4dyz orbital, which in 11a was overlapping with the π-system at C1', now shows significant overlap with the π-bond between C3' and C4' (localized primarily at C3'). This strong interaction results in a short intramolecular distance (2.29(7) Å) between these two centers, and thus is likely stronger than the ipso interaction found in 11a. There is also in-phase overlap between another lobe of 4dyz and the π-bond at C1' in this MO, suggesting that the original ipso interaction is still present in 11b (albeit to a lesser degree than in 11a). The MOs n1 and π*1 are relevant because they show strong σ-type overlaps between 4d orbitals on the metal center and C2', where a σ-bond has now formed (Figure 16). Together, these MOs reveal that the orbital overlap responsible for the ipso interaction in 11a may be important for enabling orbital overlap between C2' and 4d orbitals on the metal center, which is ultimately necessary for the formation of the σ-bound found between these two atoms in 11b.

2.3 Reaction Coordinate from 11a to 11b

A combination of transition state searches and intrinsic reaction coordinate (IRC) calculations lead to a continuous reaction pathway from 11a to 11b (Figure 17). Transition state B was located on the reaction pathway from 11a to 11b; it shows a direct 1,2-insertion of the aryl substituent into the lower ring of the ligand taking place, instead of the 1,4-insertion necessary to proceed directly from 11a to 11b. Its energy relative to 11a (ΔE = 17.7 kcal/mol) closely matches the ΔG‡ found via Eyring analysis (17.3 ± 1.3 kcal/mol) for the rearrangement of 11a to 11b, supporting the involvement of B in the rearrangement pathway.

Checking the IRC of transition state B led to new local minima on either side of the reaction coordinate instead of connecting back to 11a and 11b. As expected, 16 was found as a minimum leading to 11b and is the direct product of the 1,2-insertion depicted in B (Figure 17). 16 was calculated to be significantly higher in energy than 11b (5.4 kcal/mol), presumably due to unfavorable steric interactions between the Pd center and the adjacent aryl substituent. Proceeding forward along the reaction coordinate yielded low-lying transition state C between 16 and 11b, which depicts a simple 1,3-migration of the Pd-center via a π-allyl species (Figure 17). The small barrier (1.8 kcal/mol relative to 16) suggests that conversion of 16 to thermodynamically favored 11b should be incredibly facile and too rapid for detection of 16 by NMR. Indeed, we have never observed a second rearranged species in any rearrangement run to date. Thus, DFT calculations predict that the second half of Pathway I (Scheme 1) is the most likely pathway for the rearrangement of 11a to 11b. Following the IRC of B backward lead not to 11a but to the rotameric complex 11a' (Figure 17). Surprisingly, 11a' was calculated to have almost the same energy as 11a (−0.02 kcal/mol); calculations of an analogous cis/trans isomerization using the SPhos complex 2•Pd(Ph)Cl predicted the isomer corresponding to 11a' to be 9.7 kcal/mol higher in energy than the isomer corresponding to 11a, purportedly due to the trans influence of the phosphine ligand. Because 8 is a much larger ligand than 2, the cis/trans isomerization might be more favorable in the present case because it relieves unfavorable steric strain between the t-butyl groups and the aryl substituent, at the cost of increased interactions between the lower ring of the ligand and the aryl substituent. Transition state A was found on the IRC between 11a and 11a', and it forms by disassociation of the lower ring of the ligand and pseudo-rotation around the Pd center. The calculated barrier for this pseudo-rotation (16.5 kcal/mol) is higher than expected given that multiple oxidative addition complexes are not observable by 31P or 1H NMR at room temperature. The energy of A is likely overestimated.
due to the neglect of entropic effects in the DFT calculations, as A is more flexible than other complexes along the reaction coordinate. Solvent effects could also be crucial for stabilizing A. Nonetheless, the calculated reaction coordinate diagram supports a concerted mechanism for the insertion reaction under study, and suggests that Pathway I (Scheme 1) is operative during the rearrangement.

2.4 Reaction coordinate from 12a to 12b

In order to gain further insight into the effect of ligand structure on the dearomatization reaction, we employed the same calculations used in Figure 17 to calculate the transition states leading from the analogous RockPhos-ligated complex 12a to its rearranged isomer 12b. The results of this analysis are shown in Figure 18. DFT calculations predict 12a to be lower in energy than 12b, confirming that a substituent change in the 6-position of the phosphine-containing ring from OMe to Me is enough to destabilize the rearranged complex. A similar reaction pathway to that shown in Figure 17 was determined for the conversion of 12a to 12b: cis/trans isomerization via transition state A' to 12a', followed by 1,2-insertion via transition state B' to give 41, and finally a 1,3-shift of the Pd center (via C') to give 12b. Transition states A', B', and C' are completely analogous to A, B, and C from Figure 17. The calculated barrier for the rate-determining insertion step is higher for 12a' (20.7 kcal/mol) than for 11a' (17.7 kcal/mol). However, the cis/trans isomerization barrier is calculated to be only slightly higher for 11a compared with 11a'. Given the significantly broader \( ^{31}P \) resonance of 11a compared to 12a (Figure 5), one would expect this barrier to differ more substantially and this result may reflect the aforementioned inaccuracies in these gas phase calculations pertaining to this step of the mechanism. Nonetheless, DFT calculations suggest that the identity of the substituent in the 6-position of the phosphine-containing ring should have a significant impact on the rate and extent of rearrangement.

CONCLUSION

The presented computational and experimental work is consistent with a Pd(II)-mediated, direct aryl insertion reaction into an arene; until now, this reactivity had only been postulated as a potential pathway in some C-H arylation processes. We have found that not only is this process viable, but that it can occur under quite mild conditions in certain cases. The relief of unfavorable steric interactions between the alkyl groups on phosphorus and the aryl substituent is a powerful factor in promoting the rate and extent of rearrangement, as is the electronic nature of the aryl group. Taken together, these experimental and computational results suggest that the structural features that make bulky biaryl phosphine ligands such as 5, 8, and 10, such effective ligands for promoting challenging reductive eliminations from Pd(II) also enable the rearrangement of their oxidative addition complexes to the corresponding dearomatized isomers. This knowledge should prove useful in the design of future ligands with improved catalytic activity and, ultimately, to bulky biaryl phosphine ligands that do not show signs of rearrangement or ligand arylation in catalytic processes.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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for helpful discussions and financial assistance. The Varian spectrometers used for portions of this work were purchased with funds from the National Science Foundation (Grants CHE 980861 and DBI 9729592). One of the X-Ray diffractometers used was purchased with the help of funding from the National Science Foundation (Grant CHE 0946721). Michael Takase is acknowledged for solving several of the X-ray structures presented in this work.

REFERENCES


25. We ruled out an unlikely radical chain mechanism because the addition of BHT (5.0 eq.) had no effect on the rate of rearrangement of 11a to 11b.

26. 11a proved unstable for extended periods of time in coordinating solvents such as CD3CN and CD3NO2, probably due to gradual solvent exchange with 8.


29. The very close chemical shift to that of 28a suggests this species may be the iodide dissociated complex.


33. Despite numerous attempts, we were never able to obtain an oxidative addition complex of 6, the bulkiest known di-t-butyl biaryl phosphine ligand.

34. While more electron-rich Pd(II) complexes are more tilted with \( \beta \)BuBrettPhos than the corresponding electron-deficient complexes, the same trend does not hold true across all ligand classes (namely \( \beta \)BuXPhos).


39. The approximation that \( \Delta G \approx \Delta E \) was made in order to simplify the DFT calculations.

40. Neglecting the CHO outlier yields \( \rho = 2.48 \pm 0.24 \) and a linear fit with \( R^2 = 0.94909 \).


42. For a second-row transition element such as Pd, electron correlation and spin-orbit effects are generally weak relative to crystal field splittings and so can be neglected. See Figgis BN. Wilkinson G, Gillard RD, McCleverty JA. Ligand Field Theory, Chap. 6. Comprehensive Coordination Chemistry. 1987; Vol 1. Oxford, U.K. Pergamon:213–279.


44. The optimized structures of all intermediates and transition states shown in Figure 18 were found by starting from those found for the rearrangement of 11a and re-optimizing the geometries, as a crystal structure of 12b could not be obtained.

45. Cooling an NMR sample (CD\( _2 \)Cl\(_2\), 20 → −50 °C) of 12a revealed no interconverting species to be present. Although this result could be consistent with the interchange between 12a and 12a' being so facile as to be undetectable even at -50 °C, we believe this is highly unlikely and that it is more likely that 12a' forms in only trace amounts in solution.
Figure 1.
Biaryl phosphine ligands. Ad = adamantyl.
Figure 2.
Rearrangement of 11a to 11b.
Figure 3.
Elimination of $\mathbf{11b}$ with base to give $\mathbf{13}$ after oxidative addition.
Figure 4.
Recently reported dearomatized biaryl phosphine-ligated metal complexes.
Figure 5.  
$^3$P NMR (CD$_2$Cl$_2$) comparison of 11a and 12a.
Figure 6.
Growth of dearomatized product in the rearrangement of various $^8$Pd(Ar)Br complexes. A first-order kinetic model is overlaid for each.
Figure 7.
Hammett plot of equilibrium constants for the rearrangement of $8\cdot\text{Pd(Ar)Br}$ complexes (Table 3a).\textsuperscript{28}
Figure 8.
Pd-Ar and Pd-\emph{ipso} bond lengths, and Ar-Pd-Br bond angles for \textbf{11a}, \textbf{20a}, \textbf{22a}, and \textbf{25a} derived from X-ray crystallographic analysis.

<table>
<thead>
<tr>
<th>R</th>
<th>(\theta) (°)</th>
<th>Pd-\emph{ipso} (Å)</th>
<th>Pd-Ar (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>\textbf{n-Bu (11a)}</td>
<td>81.3(3)</td>
<td>2.50(4)</td>
<td>2.01(6)</td>
</tr>
<tr>
<td>\textbf{H (20a)}</td>
<td>80.0(0)</td>
<td>2.50(0)</td>
<td>2.01(4)</td>
</tr>
<tr>
<td>\textbf{F (22a)}</td>
<td>80.0(0)</td>
<td>2.47(0)</td>
<td>2.01(2)</td>
</tr>
<tr>
<td>\textbf{CN (25a)}</td>
<td>79.8(8)</td>
<td>2.45(2)</td>
<td>2.00(0)</td>
</tr>
</tbody>
</table>
Figure 9.
Hammett plot of the forward rate constants ($k_f$) for the rearrangement of 8•Pd(Ar)Br complexes.

$\log(k_f/k_H)$ vs. $\sigma$

$y = -1.577x + 0.0592$
$R^2 = 0.95205$
Figure 10.
Solid-state structure of $8\cdot$Pd(Ph)OTf. Ellipsoids shown at 50% probability.
Figure 11.
Intramolecular distances between the 6-substituent and the *ortho*-isopropyl group in **11a** (left) and **11b** (right). The Pd, Br, and O (in **11a**) atoms are labeled for reference. Ellipsoids shown at 50% probability.
Figure 12.
Intramolecular distance between the 6-methoxy group and one of the ortho-isopropyl groups on the lower ring of the ligand in 11b. Ellipsoids shown at 50% probability.
Figure 13.
The solid state structure of 13 shows no significant distortions of the ipso-Pd-Ar and P-Pd-Br angles from linearity and contains a more ideal square planar geometry than 11a (Figure 11).
Figure 14.
Optimized geometries of 11a (left) and 11b (right) using PBE/LANL2DZ.
Figure 15.
Theoretical (red) and experimental (blue) Hammett plot for the rearrangement of 8•Pd(Ar)Br complexes.
Figure 16.
Selected Kohn-Sham Molecular orbitals for 11a (σ₁) and 11b (σ₂, n₁, π*₁).
Figure 17.
Calculated gas phase reaction coordinate from 11a to 11b.
Figure 18.
Calculated gas phase reaction coordinate from 12a to 12b.
Scheme 1.
Plausible pathways (I–IV) for the rearrangement of 11a to 11b.
Table 1

Solvent effects on rearrangement.

<table>
<thead>
<tr>
<th>Solvent</th>
<th>$k_{eq}$</th>
<th>$k_{l}$</th>
<th>$K_{eq}$</th>
<th>$\Delta G_{exp}$ (kcal/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD$_2$Cl$_2$</td>
<td>$1.22 \pm 0.06$</td>
<td>$1.16 \pm 0.05$</td>
<td>$5.71 \pm 0.10$</td>
<td>$-1.01 \pm 0.01$</td>
</tr>
<tr>
<td>THF-d$_8$</td>
<td>$1.00 \pm 0.03$</td>
<td>$1.00 \pm 0.03$</td>
<td>$8.71 \pm 0.15$</td>
<td>$-1.26 \pm 0.01$</td>
</tr>
<tr>
<td>C$_6$D$_6$</td>
<td>$1.44 \pm 0.04$</td>
<td>$1.50 \pm 0.06$</td>
<td>$13.5 \pm 0.24$</td>
<td>$-1.51 \pm 0.01$</td>
</tr>
<tr>
<td>dioxane-d$_8$</td>
<td>$1.14 \pm 0.04$</td>
<td>$1.18 \pm 0.04$</td>
<td>$13.5 \pm 0.24$</td>
<td>$-1.51 \pm 0.01$</td>
</tr>
</tbody>
</table>

$^a$Relative to 11a in THF-d$_8$. 

\[ J \text{ Am Chem Soc. Author manuscript; available in PMC 2013 December 05.} \]
Table 2

Synthesis of 8•Pd(Ar)Br complexes.

![Diagram of reaction](image)

<table>
<thead>
<tr>
<th>Entry</th>
<th>R</th>
<th>Yield&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Entry</th>
<th>R</th>
<th>Yield&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>18a</td>
<td>N(CH&lt;sub&gt;3&lt;/sub&gt;)&lt;sub&gt;2&lt;/sub&gt;</td>
<td>57%</td>
<td>22a</td>
<td>F</td>
<td>47%</td>
</tr>
<tr>
<td>19a</td>
<td>OCH&lt;sub&gt;3&lt;/sub&gt;</td>
<td>52%</td>
<td>23a</td>
<td>Cl</td>
<td>73%</td>
</tr>
<tr>
<td>11a</td>
<td>n-Bu</td>
<td>59%&lt;sup&gt;15&lt;/sup&gt;</td>
<td>24a</td>
<td>CHO</td>
<td>67%</td>
</tr>
<tr>
<td>20a</td>
<td>H</td>
<td>66%</td>
<td>25a</td>
<td>CN</td>
<td>66%&lt;sup&gt;13&lt;/sup&gt;</td>
</tr>
<tr>
<td>21a</td>
<td>Ph</td>
<td>73%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup>Reaction conditions: 1.0 eq. (1,5-cyclooctadiene)Pd(CH<sub>2</sub>TMS)<sub>2</sub>, 1.0 eq. 8, 1.1–5.0 eq. aryl bromide, cyclohexane, 12 hours.

<sup>b</sup>Isolated yields, not optimized.
Table 3

a. Aryl substituent effects on rearrangement (thermodynamic parameters).

<table>
<thead>
<tr>
<th>Entry</th>
<th>R</th>
<th>σ</th>
<th>$K_{eq}$</th>
<th>$\Delta G_{exp}$ (kcal/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18a</td>
<td>$\text{N(CH}_3\text{)}_2$</td>
<td>0.83</td>
<td>(40.5)$^a$</td>
<td>(−2.2)$^a$</td>
</tr>
<tr>
<td>19a</td>
<td>$\text{OCH}_3$</td>
<td>0.27</td>
<td>19.4 ± 0.34</td>
<td>−1.73 ± 0.01</td>
</tr>
<tr>
<td>11a</td>
<td>$\text{n-Bu}$</td>
<td>0.16</td>
<td>8.71 ± 0.15</td>
<td>−1.26 ± 0.01</td>
</tr>
<tr>
<td>20a</td>
<td>H</td>
<td>0.00</td>
<td>4.32 ± 0.08</td>
<td>−0.85 ± 0.01</td>
</tr>
<tr>
<td>21a</td>
<td>Ph</td>
<td>0.01</td>
<td>3.24 ± 0.06</td>
<td>−0.68 ± 0.01</td>
</tr>
<tr>
<td>22a</td>
<td>F</td>
<td>0.06</td>
<td>3.61 ± 0.06</td>
<td>−0.75 ± 0.01</td>
</tr>
<tr>
<td>23a</td>
<td>Cl</td>
<td>0.23</td>
<td>3.24 ± 0.06</td>
<td>−0.23 ± 0.01</td>
</tr>
<tr>
<td>24a</td>
<td>CHO</td>
<td>0.42</td>
<td>0.24$^b$</td>
<td>0.83 ± 0.01</td>
</tr>
<tr>
<td>25a</td>
<td>CN</td>
<td>0.66</td>
<td>0.09$^b$</td>
<td>0.83 ± 0.01</td>
</tr>
</tbody>
</table>

b. Aryl substituent effects on rearrangement (kinetic parameters).

<table>
<thead>
<tr>
<th>Entry</th>
<th>R</th>
<th>σ</th>
<th>$K_{f+r}$</th>
<th>$K_{f}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>18a</td>
<td>$\text{N(CH}_3\text{)}_2$</td>
<td>0.83</td>
<td>&gt;10</td>
<td>&gt;11</td>
</tr>
<tr>
<td>19a</td>
<td>$\text{OCH}_3$</td>
<td>0.27</td>
<td>3.35 ± 0.13</td>
<td>3.93 ± 0.14</td>
</tr>
<tr>
<td>11a</td>
<td>$\text{n-Bu}$</td>
<td>0.16</td>
<td>1.50 ± 0.05</td>
<td>1.66 ± 0.06</td>
</tr>
<tr>
<td>20a</td>
<td>H</td>
<td>0.00</td>
<td>1.00 ± 0.03</td>
<td>1.00 ± 0.04</td>
</tr>
</tbody>
</table>
b. Aryl substituent effects on rearrangement (kinetic parameters).

<table>
<thead>
<tr>
<th>Entry</th>
<th>R</th>
<th>σ</th>
<th>$K_{f+r}$</th>
<th>$K_f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>21a</td>
<td>Ph</td>
<td>0.01</td>
<td>1.02 ± 0.04</td>
<td>0.96 ± 0.03</td>
</tr>
<tr>
<td>22a</td>
<td>F</td>
<td>0.06</td>
<td>1.01 ± 0.05</td>
<td>0.97 ± 0.03</td>
</tr>
<tr>
<td>23a</td>
<td>Cl</td>
<td>0.23</td>
<td>0.86 ± 0.04</td>
<td>0.63 ± 0.02</td>
</tr>
<tr>
<td>24a</td>
<td>CHO</td>
<td>0.42</td>
<td>0.99 ± 0.05</td>
<td>0.24 ± 0.01</td>
</tr>
<tr>
<td>25a</td>
<td>CN</td>
<td>0.66</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^a$From a first-order kinetic model

$^b$Estimated error is less than ± 0.01.

$^c$Relative to 20a in THF-d$_8$.

$^d$Kinetics unreliable.
Halide Effects on Rearrangement.

Table 4

<table>
<thead>
<tr>
<th>Entry</th>
<th>$K_{eq}^{c}$</th>
<th>$k_f^{c}$</th>
<th>$k_c^{c}$</th>
<th>$\Delta G_{exp}$ (kcal/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>26a</td>
<td>2.84 ± 0.08</td>
<td>2.18 ± 0.07</td>
<td>2.15 ± 0.04</td>
<td>−0.44 ± 0.01</td>
</tr>
<tr>
<td>11a</td>
<td>1.00 ± 0.03</td>
<td>1.00 ± 0.03</td>
<td>8.71 ± 0.15</td>
<td>−1.26 ± 0.01</td>
</tr>
<tr>
<td>28a</td>
<td>.d</td>
<td>.d</td>
<td>0.04e</td>
<td>1.87 ± 0.01</td>
</tr>
</tbody>
</table>

$^a$Isolated yield, prepared in the same manner as in Table 2.

$^b$Decomposed in solution.

$^c$Relative to 11a in THF-d$_8$.

$^d$Kinetics unreliable due to small change in [28a] over time.

$^e$Value in C$_6$D$_6$, estimated error is less than ± 0.01.
Phosphine Substituent Effects on Rearrangement.

<table>
<thead>
<tr>
<th>Entry</th>
<th>R</th>
<th>Yield</th>
<th>$k_{f+}^b$</th>
<th>$k_f^b$</th>
<th>$K_{eq}$</th>
<th>$\Delta G_{exp}^c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>29a</td>
<td>Cy</td>
<td>72%</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>11a</td>
<td>t-Bu</td>
<td>59%</td>
<td>$1.00 \pm 0.03$</td>
<td>$1.00 \pm 0.03$</td>
<td>$8.71 \pm 0.15$</td>
<td>$-1.26 \pm 0.01$</td>
</tr>
<tr>
<td>30a</td>
<td>Ad</td>
<td>37%</td>
<td>$0.87 \pm 0.04$</td>
<td>$0.87 \pm 0.03$</td>
<td>$9.00 \pm 0.16$</td>
<td>$-1.28 \pm 0.01$</td>
</tr>
</tbody>
</table>

a Isolated yield, prepared in the same manner as in Table 2.

b Relative to 11a in THF-d$_8$.

c In kcal/mol.

d Rearranged product not observed. Ad = adamantyl.
Ligand substituent effects on rearrangement.

<table>
<thead>
<tr>
<th>Entry</th>
<th>R</th>
<th>R'</th>
<th>Yield</th>
<th>$K_{f+e}$</th>
<th>$K_h^b$</th>
<th>$K_{eq}$</th>
<th>$\Delta G_{exp}^c$</th>
</tr>
</thead>
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<tr>
<td>11a</td>
<td>OMe</td>
<td>OMe</td>
<td>59%</td>
<td>1.00 ± 0.03</td>
<td>1.00 ± 0.03</td>
<td>8.71 ± 0.15</td>
<td>−1.26 ± 0.01</td>
</tr>
<tr>
<td>11b</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12a</td>
<td>OMe</td>
<td>Me</td>
<td>76%</td>
<td>.d</td>
<td>.d</td>
<td>0.19e</td>
<td>0.97 ± 0.01</td>
</tr>
<tr>
<td>12b</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>31a</td>
<td>H</td>
<td>H</td>
<td>77%</td>
<td>3.77 ± 0.54</td>
<td>0.87 ± 0.07</td>
<td>0.26e</td>
<td>0.78 ± 0.01</td>
</tr>
<tr>
<td>31b</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>32a</td>
<td>OMe</td>
<td>H</td>
<td>58%</td>
<td>.f</td>
<td>.f</td>
<td>10.0 ± 0.2</td>
<td>−1.34 ± 0.01</td>
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<tr>
<td>32b</td>
<td></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>33a</td>
<td>Me</td>
<td>H</td>
<td>35%</td>
<td>.f</td>
<td>.f</td>
<td>15.0 ± 0.3</td>
<td>−1.58 ± 0.01</td>
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<td>33b</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>34a</td>
<td>H</td>
<td>Me</td>
<td>34%</td>
<td>.d</td>
<td>.d</td>
<td>0.01e</td>
<td>2.68 ± 0.01</td>
</tr>
<tr>
<td>34b</td>
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<td></td>
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<td></td>
</tr>
</tbody>
</table>

\(^a\) Isolated yields; prepared in the same manner as in Table 2.

\(^b\) Relative to 11a in THF-d₈.

\(^c\) In kcal/mol.

\(^d\) Kinetics unreliable.

\(^e\) Estimated error is less than ± 0.01.

\(^f\) Obtained at equilibrium.
Table 7

Equilibrium parameters for the rearrangement of various aryl-substituted complexes derived from 5 and 10.

<table>
<thead>
<tr>
<th>a</th>
<th>b</th>
<th>R</th>
<th>Yield</th>
<th>$K_{eq}$</th>
<th>$\Delta G_{exp}$ (kcal/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>35a</td>
<td>35b</td>
<td>N(CH$_3$)$_2$</td>
<td>77%</td>
<td>2.15 ± 0.04</td>
<td>−0.45 ± 0.01</td>
</tr>
<tr>
<td>31a</td>
<td>31b</td>
<td>$\sigma$-Bu</td>
<td>77%</td>
<td>2.26$^b$</td>
<td>0.78 ± 0.01</td>
</tr>
<tr>
<td>36a</td>
<td>36b</td>
<td>H</td>
<td>70%</td>
<td>0.11$^b$</td>
<td>1.28 ± 0.01</td>
</tr>
<tr>
<td>37a</td>
<td>37b</td>
<td>CN</td>
<td>67%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>a</th>
<th>b</th>
<th>R</th>
<th>Yield</th>
<th>$K_{eq}$</th>
<th>$\Delta G_{exp}$ (kcal/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>38a</td>
<td>38b</td>
<td>N(CH$_3$)$_2$</td>
<td>75%</td>
<td>1.08 ± 0.02</td>
<td>−0.05 ± 0.01</td>
</tr>
<tr>
<td>12a</td>
<td>12b</td>
<td>$\sigma$-Bu</td>
<td>76%</td>
<td>0.19$^b$</td>
<td>0.97 ± 0.01</td>
</tr>
<tr>
<td>39a</td>
<td>39b</td>
<td>H</td>
<td>76%</td>
<td>0.08$^b$</td>
<td>1.47 ± 0.01</td>
</tr>
<tr>
<td>40a</td>
<td>40b</td>
<td>CN</td>
<td>70%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^a$Isolated yields; prepared in analogy to Table 2.

$^b$Estimated absolute error is less than 0.01.

$^c$Rearranged species not detected by $^1$H NMR.
Table 8

Experimental $\Delta G$ and calculated $\Delta E$ values for various $\text{8-Pd(Ar)Br}$ complexes.

<table>
<thead>
<tr>
<th>a</th>
<th>b</th>
<th>R</th>
<th>$\sigma$</th>
<th>$\Delta G_{\text{exp}}$ (kcal/mol)$^a$</th>
<th>$\Delta E$ (kcal/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18a</td>
<td>18b</td>
<td>$\text{N(CH}_3\text{)}_2$</td>
<td>-0.83</td>
<td>($-2.4$)$^b$</td>
<td>-2.28</td>
</tr>
<tr>
<td>19a</td>
<td>19b</td>
<td>$\text{OCH}_3$</td>
<td>-0.27</td>
<td>-1.73 ± 0.01</td>
<td>-1.35</td>
</tr>
<tr>
<td>11a</td>
<td>11b</td>
<td>$\text{n-Bu}$</td>
<td>-0.16</td>
<td>-1.26 ± 0.01</td>
<td>-0.43</td>
</tr>
<tr>
<td>20a</td>
<td>20b</td>
<td>H</td>
<td>0.00</td>
<td>-0.85 ± 0.01</td>
<td>0.02</td>
</tr>
<tr>
<td>21a</td>
<td>21b</td>
<td>Ph</td>
<td>0.01</td>
<td>-0.68 ± 0.01</td>
<td>0.40</td>
</tr>
<tr>
<td>22a</td>
<td>22b</td>
<td>F</td>
<td>0.06</td>
<td>-0.75 ± 0.01</td>
<td>-0.03</td>
</tr>
<tr>
<td>23a</td>
<td>23b</td>
<td>Cl</td>
<td>0.23</td>
<td>-0.23 ± 0.01</td>
<td>1.17</td>
</tr>
<tr>
<td>24a</td>
<td>24b</td>
<td>CHO</td>
<td>0.42</td>
<td>0.83 ± 0.01</td>
<td>2.93</td>
</tr>
<tr>
<td>25a</td>
<td>25b</td>
<td>CN</td>
<td>0.66</td>
<td>1.43 ± 0.01</td>
<td>2.46</td>
</tr>
</tbody>
</table>

$^a$In THF-d$_8$.

$^b$Estimated using a first-order kinetic model.