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Transmetalation from B to Rh in the course of the catalytic asymmetric 1,4-addition reaction of phenylboronic acid to enones: A computational comparison of diphosphane and diene ligands

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Transmetalation is a key elementary reaction of many important catalytic reactions. Among those, the 1,4-addition of arylboronic acids to organic acceptors such as α,β-unsaturated ketones has emerged as one of the most important methods for asymmetric C-C bond formation. A key intermediate for the B-to-Rh transfer arising from quaternization on the boronic acid by a Rh-bound hydroxide (the active catalyst) has been proposed. Herein, DFT calculations (IEFPCM/PBE0/DGDZVP level of theory) establish the viability of this proposal, and characterize the associated pathways. The delivery of the phenylboronic acid in the orientation suited for the B-to-Rh transfer from the very beginning is energetically preferable, and occurs with expulsion of Rh-coordinated water molecules. For the bulkier binap ligand, the barriers are higher (particularly for the phenylboronic acid activation step) due to a less favourable entropy term to the free energy, in accordance with the experimentally observed slower transmetalation rate.

Introduction

Among organoboron compounds, boronic acids1 have become the most prominent choice for uses in catalysis2 due to their easy accessibility, air- and moisture-tolerance and low toxicity. The key elementary reaction that enables such applications is transmetalation (TM) from B to the catalytically active transition metal.3 For instance, in the Nobel Prize-winning Suzuki-Miyaura reaction4 (Scheme 1) oxidative addition (OA) of the organic halide substrate into the Pd(0) catalyst generates a square-planar aryl-Pd(II) halide, which undergoes TM with a wide range of organoboron compounds.5 Reductive elimination (RE) from the diaryl Pd(II) intermediate formed after TM completes the cycle. Improving our mechanistic understanding of TM would enable better catalytic cycle design. Not surprisingly, TM to Pd(II) intermediates related to the Suzuki-Miyaura catalytic cycle is well studied by experimental6,7 and computational8,9 mechanistic approaches. Similarly, the catalytic cycle10 for 1,4-addition of arylboronic acids11 (e.g., 1; Scheme 2) to organic electrophiles such as 2-cyclohexenone (2) involves transmetalation to a square-planar Rh(I) centre (Scheme 1). However, experimental studies on Rh transmetalation are scarce.12 Even though recently a significant attention has been devoted to understanding the enantioselectivity controlling carborhodation step in the 1,4-addition reaction by means of density functional calculations,13 no exact studies exist for the preceding, turnover-determining transmetalation step.14,15

Following pioneering studies by Miyaura et al. in 1997,16 the groups of Hayashi and Miyaura jointly presented in 199817 the first highly enantioselective 1,4-addition of arylboronic acids mediated by a [(binap)Rh(I)]+ catalyst (binap = 2,2'-).
bis(diphenylphosphino)-1,1'-binaphthyl, I). In the years after, the Hayashi-Miyaura reaction and related Rh(I)-catalyzed arylation have become one of the most important catalytic asymmetric manifolds. In 2003, Hayashi group presented a conceptually novel ligand class,28 chiral, C₂-symmetric bidentate olefins based on the bicyclo[2.2.2]octa-2,5-diene (bod) framework such as II. Simultaneously and independently, Carreira group developed C₂-symmetric derivatives for the Ir-catalyzed π-allyl substitution.21 Detailed kinetic measurements showed that: 1) the transmetalation is the rate-determining for the whole cycle; and 2) diene ligands are more reactive than diphosphines: the addition of PhB(OH)₂(I) to 2-cyclohexeneone (2) requires 3 h at 40°C to produce 97% yield of 3 (96%ee) with Phbod as the ligand,18 as opposed to 5 h at 100°C to 93% of 3 (97%ee) with bnip with similar excess of 1 (2-2.5 equiv.). These examples demonstrate the importance of transmetalation step for the overall success of the asymmetric arylation. Herein we present a comparative study of transmetalation for ligands I and II in the course of the asymmetric 1,4-addition reaction.

20 Results and discussion

Computational methods

Exploration of key stationary points along the potential energy hyper-surface (PEHS) for the transmetalation reaction was performed with Gaussian09 software suite using the standard Perdew-Burke-Ernzerhof generalized gradient approximation (GGA) DFT functional hybrid with 25% Hartree-Fock (HF) exchange (PBE0).24 The DeGauss full-electron, DFT-optimized basis set designed for low basis set superposition error (BSSE) (DGDZVP)25 was chosen to build the atomic orbitals. This basis set includes valence shell polarization functions on both heavy atoms and hydrogen and supports quantitative analysis of the electron density distribution by Bader's Atoms-In-Molecules (AIM) method (see below). Structural optimization of minima was performed in implicit 1,4-dioxane employing the integral equation formalism polarisable continuum model (IEFPCM).27 Structural optimizations cut-off values for Rh complexes were as follows: for maximum force: 0.0001500, root-mean-square (RMS) force: 0.0001000, maximum displacement: 0.001800, and RMS displacement: 0.001200. Transition state search was performed by relaxed potential energy scan of the relevant bonds of the transition state guess generated thereby. The final geometry optimization was combined with a frequency calculation (under the ideal gas approximation). For reasons of computational efficiency (DFT methods scale roughly to the 3rd power of the basis functions number), detailed characterization of the transmetalation pathways was conducted only for ligand II, followed by calculations of the stationary points along only the preferred pathway for ligand I. The [(ligand)Rh(OH)⁺PhB(OH)₂⁺] composition requires 508 and 908 basis functions for ligands II and I, respectively, with DGDZVP basis set. AIM analyses were performed using AIMAll software suite (version 14.06.21) with the default parameters.28

Transmetalation with diene ligands

Transmetalation being a transfer of a Ph residue from Rh to B presupposes the formation of a single entity incorporating these 3 components. In 2004, Miyaura proposed the adduct of M-OH and PhB(OH)₂ (neutral for M = Rh(I) and cationic for M = Pd(II), respectively), in which the boron is tetracoordinate, as the key transmetalation intermediate for the 1,4-addition reaction (Figure 1a).29 The experimental mechanistic studies have established that the active catalyst most likely is the [(L)Rh(OH)] (L = bidentate ligand) species, which is sufficiently basic to quantize PhB(OH)₂ giving rise to the Miyaura's proposed intermediate. This is consistent with the experimental observation that the reaction proceeds to completion even without adding an external base.17, 30 Initial modelling of PhB(OH)₂ showed that there are 3 conformations which can be distinguished by the position of the H atom relative to the Ph ring - on the same (in) or the opposite (out) side across the B-OH bond (Figure 1b). The "in/out" conformation (1a) is the most stable. Expecting this stabilization to be at least partially preserved along the pathway, we restricted our study to this conformation only for reasons of computational efficiency. The initial association in the TM profile (Figure 1c, 4-12) gives rise to an H-bonded adduct (5) of the catalyst [(L)Rh(OH)] (4) and 1a. Because the two OH groups in 1a are non-equivalent, there are two possible pathways depending on whether the "in" or the "out" OH group is engaged. The H-bond is confirmed by the AIM analyses of the electron density finding BCPs between O₁ and H₂ (ρ₂₅₀ = 0.0669 for 5a and 0.0743 for 5b; for comparison, the ρ₅₀ for the O₁-H₁ "whole" bond are 0.3442 and 0.3433, respectively) (Figure 2). The H-bond formation is accompanied by lengthening of the Rh-O₁ distance from 1.981 Å in 4 to 2.051 Å in 5a and 2.047 Å in 5b, respectively. The H-bond length (H₂-O₁) is 1.560 Å in 5a and 1.505 Å in 5b. In the initial adduct in the "in" pathway (5a), a weak interaction between Rh and C₂ (ρ₂₅₀ = 0.0443) was detected by AIM analysis (compare to ρ₂₅₀ = 0.1248 for the Rh-C₁ bond in 11). The Rh-C₂ distance is 2.444 Å. In contrast, the analogous "out" structure 5b has the second B-OH group weakly coordinating (ρ₂₅₀ = 0.0562) the Rh centre positioned 2.229 Å away. Structure 5b is considerably more stable than 5a (DG = −1.1 vs. −6.0 kcal mol⁻¹, respectively). The pathway continues by activation of PhB(OH)₂ by the Rh-bound OH group executed by a sliding/rotating motion of the B centre towards O₁. The respective TSs for this step (6) are much closer in energy, with the "out" structure (6b) being higher in energy than the "in" (6a) (DG = 4.4 vs. 3.0 kcal mol⁻¹, respectively). The barrier for the "out" activation is 15.5 kcal mol⁻¹ compared to 10.4 kcal mol⁻¹ for the "in". It appears that a Curtin-Hammett situation is in place: the less stable intermediate (5a) reacts faster. TS 6a collapses to intermediate 9a. The B-O₁ distance shortens from 3.226 to 2.388 Å to 2.541 Å going in the sequence 5a→6a→9a. In 6a, the H-bond is replaced by a weak O₁-B interaction (ρ₂₅₀ = 0.0266), which strengthens in 9a (ρ₂₅₀ = 0.1829), corresponding to the new B-O bond. In the intermediate 9a, the weak Rh-C₂ interaction is replaced by a new Rh-C₁ weak (ρ₂₅₀ = 0.0546) interaction as a consequence of the slight rotation of 1b in the sequence 5a→6a→9a. In the first intermediate of the "out" pathway (5b), PhB(OH)₂ lies in the plane of the Rh coordination square.
quaternization of the boron from planar (sp²) to tetrahedral (sp³) upon attack by the Rh-bound OH causes the Ph ring to turn out of this plane. TS 6b collapses to the intermediate 7, in which two OH groups coordinate Rh centre. The Rh-O distances are virtually identical (2.134 and 2.133 Å) and PhB(OH)₂ is almost symmetrical with respect to the diene ligand: the diene CH₂-CH₂ bridge and the B-C₁ bond are perfectly aligned yet the Ph ring is slightly tilted due to avoiding the clash with the Ph ring on the chiral diene ligand. This is confirmed by the equal bond lengths and electron densities (2.133 and 2.134 Å, and ρ̃ = 0.0769 and 0.0758 respectively). In this structure, the Ph group sits perpendicularly to the Rh coordination plane occupied by the two diene and two OH groups. Attempts to locate a Ph transfer TS from this structure showed that conformational rearrangement via rotation around the Rh-O₁ bond, which moves the Ph group in the coordination plane, is preferred. In view of the importance of this process, we located the corresponding torsional TS 8 (ΔG = −2.5 kcal mol⁻¹), wherein O₂ moves out and the Ph group moves in the Rh coordination site. Accordingly, the Rh-O₂ bond lengths from 2.134 (in 7) to 2.574 Å; the corresponding loss of bonding is evident by comparing the ρ̃ value decreasing from 0.0758 (in 7) to 0.0322. TS 8 collapses to intermediate 9b, very similar to the corresponding intermediate of the TM sequence to −16.2 kcal mol⁻¹. TSFless dissociation of B(OH)₂ (13a) completes the TM sequence, giving a tricoordinate Rh-Ph intermediate 12, which is free to coordinate an acceptor molecule such as 2 and continue the reaction. ΔG drops by a net of 2.8 kcal mol⁻¹ to −12.2 kcal mol⁻¹ balancing out the large loss of Rh(OH)-B(OH)₂ coordination energy (ΔH term is highly endothermic, from −21.1 to −12.4 kcal mol⁻¹) with an even larger entropy gain. In 11, two of the 3 hydrogen atoms adopt syn conformation (13a). The alternative conformation 13b, in which all 3 H atoms are mutually "anti" is considerably more stable (by 4.0 kcal mol⁻¹). Factoring this conformational stabilization in lowers the total ΔG of the TM sequence to −16.2 kcal mol⁻¹.

Overall, the energies of the TS suggest that: 1) the "in" pathway having the smallest energy span is preferred, and 2) TS 8 provides a low energy switch from the "out" into the "in" pathway. Progressing along the reaction coordinate, the Rh-C₁ distance grows progressively shorter: in the "in" pathway, 2.728 → 2.505 → 2.356 → 2.188 → 2.040 → 2.006 Å in the sequence 5a → 6a → 9a → 10 → 11; in the "out" pathway, 4.746 → 4.152 → 3.643 → 2.634 → 2.407 Å in the sequence 5b → 6b → 7 → 8 → 9b. Similarly, the B-C₁ distance grows...
Figure 2. AIM plots (PCM(1,4-dioxane)/PBE0/DGDZVP level of theory) for key stationary points along the reaction coordinate in the transmetalation reaction profile (Figure 1). The critical points (CP) are shown as follows: bond (B), in red; ring, in green; cage, in blue. Selected BCP $\rho_b$ values (red), bond lengths, bond angles and torsional angles (blue) are also shown.

progressively longer: in the "in" pathway, $1.584 \rightarrow 1.590 \rightarrow 1.647 \rightarrow 2.050 \rightarrow 3.128 \rightarrow \infty$ Å in the sequence 5a→6a→9a→10→11→12; in the "out" pathway, $1.570 \rightarrow 1.567 \rightarrow 1.615 \rightarrow 1.640 \rightarrow 1.644$ Å in the sequence 5b→6b→7→8→9b. The "in" pathway from the very beginning delivers the Ph-B group in the correct orientation hence the overall distance travelled by the reacting atoms is smaller than in the alternative "out" pathway. This motion is ultimately governed by the key Rh-O$_1$-B-C$_1$ dihedral angle (D1). Due to the $C_2$ ligand symmetry, only two, pathway-determining alternatives − syn for "in" (Ph group in the Rh coordination plane) vs. anti for "out" (Ph group perpendicular to the Rh coordination plane) − are possible,
as it can be most clearly seen in 'Miyaura intermediate'. Along the pathway, D1 adopts values 39→31→−5→−24° in the sequence 5a→6a→9a→10. and 158→−109→−97→−54→4→−24° in the sequence 5b→6b→7→8→9b→10.

Transmetalation in the presence of a Rh-coordinated water molecule

The active catalyst [(L)Rh(OH)] has been shown to exist in fast equilibrium with the corresponding tetracoordinate µ-OH dimer. Conceivably, a water molecule from the water co-solvent can act as the 4th ligand, forming an aqua complex of the type [(L)Rh(OH)(OH)] which is 6.0 kcal mol$^{-1}$ less stable than the corresponding tetracoordinate, square-planar aqua complex. It is to be expected that the aqua complex formation will have an effect on the subsequent transmetalation step. Therefore, we calculated the transmetalation mechanism in the presence (Figure 3, 14-21) of a σ-coordinated water molecule. For the (S)-Phbod ligand ((S)-II), the tri-coordinate [(S)-II]Rh(OH)] (4) is 6.0 kcal mol$^{-1}$ less stable than the corresponding tetracoordinate, square-planar aqua complex 14. The presence of the water molecule in the coordination sphere of the metal complicates the profile by lowering of the symmetry. This in turn affects the number of possible profiles expressed by the number of unique conformations arising from rotation around the D1 coordinate. This effect is easiest to discern in the quarternized Phb(OH)$_2$ 17 ('Miyaura's intermediate'). Total of 3 conformers were found: 17a (∆G = −12.9 kcal mol$^{-1}$) having D1 value of −13° (conf1), 17b (∆G = −12.2 kcal mol$^{-1}$) having D1 value of 62° (conf2), and 17c (∆G = −11.3 kcal mol$^{-1}$) having D1 value of −178° (conf3). These 3 conformers lie on the reaction coordinates of 3 pathways, which will be referred to in analogous manner, "conf1", "conf2" and "conf3". In 17a, Rh is coordinated with O$_7$ and C$_7$(Ph) whereas in 17b and c, with O$_7$ and O$_7$. The Rh-O$_7$ bond lengths are almost identical in the 3 structures (2.131, 2.127, and 2.136 Å for 17a, b, and c, respectively) (Figure 4). The Rh-C$_7$ bond length in 17a is 2.362 Å. The Rh-coordinated H$_2$O molecule (Rh-O$_7$ bond lengths 2.183 and 2.193 Å in 17b and c, respectively) engages in additional H-bonding with one of the two B-OH groups forming a 7-membered chelate. The H-atom of H$_2$O positioned closer to Rh (H$_7$) acts as the donor and O$_7$ as the acceptor; the corresponding H-O$_7$ distances are 1.551 and 1.559 Å. In contrast, the H$_2$O molecule is displaced from the coordination sphere of the metal by 1a forming a 5-member chelate with O$_7$ and C$_7$ atoms. However, the H$_2$O molecule still does not leave the scene by forming an analogous H$_7$ (donor)···O$_7$ (acceptor) H-bond (O$_7$-H$_7$ inter-atomic distance is 1.818 Å). The "Miyaura's intermediates" 17a, b, and c are produced upon the collapse of the quartetization TS 16a, b, and c for "conf1", "conf2" and "conf3" pathways, respectively. The B-O$_7$ bonds in the TSs are considerably longer (2.760, 2.647, and 2.183 Å for 17a, b, and c, respectively) than in the intermediates that follow (1.539, 1.541, and 1.527 Å in 17a, b, and c, respectively). In the "conf1" pathway, the H$_2$O molecule is still coordinated to Rh (Rh-O$_7$ bond length of 2.220 Å) and the

Figure 3. An alternative transmetalation reaction profile (PCM(1,4-dioxane, 303.15 K)/PBE0/DGDZVP level of theory) to account for Rh(I) aqua complex formation showing ∆G and ∆H (italics) of stationary points (in green) relative to the sums of the corresponding values for 4, 1b, and H$_2$O. The reaction coordinate is shown schematically at the top.
Figure 4. Structure plots (PCM(1,4-dioxane)/PBE0/DGDZVP level of theory) for selected key stationary points along the reaction coordinate in the hydrated transmetalation reaction profile (Figure 3). Selected bond lengths, bond angles and torsional angles (blue) are shown.

H₃···O₁ H-bond persists (bond length of 1.736 Å). That signifies that B quarternization in the "conf1" pathway proceeds with an expulsion of H₂O molecule from the coordination sphere of the metal. The H-bonding pattern is considerably rearranged in the "conf2" and "conf3" pathways. In the first case, there are two H bonds, H₂···O₁ (bond length of 1.846 Å) and H₃···O₁ (bond length of 2.082 Å). In the second case, there are two analogous H bonds, H₂···O₁ (bond length of 1.909 Å) and H₃···O₁ (bond length of 1.987 Å). TSs 16 arise from the initial adducts 15. The complex 15a in the "conf1" pathway features a 6-membered chelate network tightly held together by two rather short H-bonds, H₄···O₁ (bond length of 1.399 Å) and H₃···O₁ (bond length of 1.703 Å). In the sliding motion that takes place during the B quarternization, the H₄···O₁ H bond is lost due to the O₁ atom sliding forward and the O₃···H₂ bond rotating out. The second H-bond persists into the TS 16a and onto the subsequent intermediate 17a. On the other hand, in the other two pathways the original active catalyst hydrate structure (14) is largely preserved upon coordination of PhB(OH)₂. In 14, the Rh-O₁ (the anionic oxygen) bond length is 2.038 Å and the Rh-O₂ (the neutral oxygen) bond length is 2.251 Å, as expected. The H atom on the water molecule which is proximal to the hydrate (H₂) is H-bonded to the latter (1.769 Å). The H-bond causes a lengthening of the O₂···H₂ bond (0.996 Å) compared to the O₂···H₁ bond (0.969 Å). Going to 15b and 15c, one of the oxygen atoms from PhB(OH)₂ forms a H-bond with H₂ (bond lengths 2.078 and 1.841 Å in 15b and c, respectively). There is a major topological difference between the two intermediates in the sense that in 15b the PhB(OH)₂ is "wrapped around" the Rh centre, whereas in 15c it is extended out.

Continuing from 17, B-to-Rh transfer takes place. This is not possible from "conf3", because the Ph group is on the opposite side of the Rh atom; from this conformation, the pathway merges with either conf1 or conf2 via rotation around the key D₁ torsional angle. As it was demonstrated earlier, this conformational change is expected to be at least 3–4 kcal mol⁻¹ lower than the ensuing TS 18, hence the corresponding torsional TSSs were not calculated. The conf1 pathway proceeds via TS 18a, which is an identical structural analogue of TS 10, with exception of a water molecule H-bonded to the nascent B(OH)₃ molecule; the O₃···H₃ distance being 1.857 Å. The Rh-C₁ and B-C₂ bond lengths are 2.167 and 2.099 Å, respectively, very similar to those in TS 10. Interestingly, for "conf2" pathway a separate Rh-to-B transfer TS (18b) was found, with the transfer occurring at ~30° angle to the Rh coordination plane. In this TS, the water molecule, just as in the structures preceding it, maintains coordination to Rh; the Rh-O₂ bond length is 2.218 Å. The B atom is also located at ~30° angle from the Rh coordination plane.
on the opposite side to Ph. The Rh-C₁ and B-C₁ bond lengths are 2.249 and 2.116 Å, respectively. The H₃⋯O₃ bond is rather short (1.641 Å). TSs 18 collapse to Rh-Ph species additionally coordinated with H₂O (“conf1”) or B(OH)₃ (“conf2”). The third particle, B(OH)₃ and H₂O in each respective case is only attached by an H bond and is expected to dissociate with diffusion-controlled rate. In the “conf1” pathway, this produces 11 from the non-hydrated pathway, that is, the two pathways merge herein. In the case of “conf2”, a new [(S)-H]Rh(OH₂)Ph complex (21) is produced; the Rh-C₁ bond is 2.044 Å, and the Rh-O₂ bond is 2.249 Å. Just as in the non-hydrated pathway, a conformational change in B(OH)₃ from “syn” (13a) to “anti” (13b) conformation lowers the end-point ΔG by 4.0 kcal mol⁻¹. Interestingly, if analogous conformational change takes place in the preceding intermediate (20a to 20b), it actually leads to increase of ΔG by 3.4 kcal mol⁻¹.

An overall assessment of the hydrated profile reveals two important points. First, within the hydrated profile, the “conf1” pathway, which is the most structurally similar to the non-hydrated profile “in” pathway, is the most thermodynamically preferred by virtue of having the lowest free-energy span. Second, the barriers within the hydrated profile are significantly higher but the intermediates are significantly lower in energy than the non-hydrated one. This implies that the transmetalation proceeds by the non-hydrated profile, with the hydrated intermediates acting as off-cycle intermediates being in rapid equilibrium with their non-hydrated counterparts. This can be rationalized by considering that from the 4 coordination sites available, 2 are permanently locked by the diene ligand, and two are needed to accommodate Ph and B(OH)₃, hence the “dehydrating” of the hydrated pathway by expulsion of a water molecule from the coordination sphere of the metal in the sequence 15a→16a→17a.

**Transmetalation of BINAP-Rh catalysis**

Having established the validity of the non-hydrated “in” pathway as the main transmetalation mechanism, we calculated this pathway for the classic [Rh(binap)] catalyst (Figure 5a).

![Figure 5](image_url)
Comparison of the stationary points Gibbs energies across the pathway reveals important differences. The barriers for both phenylboronic acid activation and B-to-Rh transfer are much higher for the bulkier binap ligand than for the smaller Phbod, especially the former (ΔG for TSs 24 and 6a are 15.3 vs. 4.4 kcal mol\(^{-1}\), respectively). This destabilization persists also in the intermediates on either side of this TS (23 and 25), being considerably more endergonic for ligand I versus II. This effect is counter-intuitive considering that the boron activation occurs relatively far from the ligand bulk and the basicity of the Rh-bound OH is expected to be enhanced due to the higher donating power of the phosphone. Comparison of the ΔH values reveals that this effect is due primarily to the entropy term. Similar, but smaller effect occurs at the B-to-Rh transfer TS (ΔG for I0 vs. 26 are 2.0 and 8.2 kcal mol\(^{-1}\), respectively). The ligand change does not affect the reaction thermodynamically, however, ΔG being –16.7 and –16.2 kcal mol\(^{-1}\) for ligands I and II, respectively. The –TΔS term at this point is close to 0, which strengthens the argument of entropy-lowered transmetalation rate for I. The computations, therefore, agree well with the experimentally observed slower reaction rate (attributed to slower transmetalation) for Rh-catalysts carrying ligand I versus II. However it should be pointed out that a direct comparison between ligands I and II is difficult due to the very different reaction conditions (absence and presence of an external base, respectively). Accurate kinetic studies have shown that under the same conditions, the 1,4-addition to methyl vinyl ketone, a very active substrate, catalyzed by [binap]RhOH] is just 1 order of magnitude slower than when catalyzed by [cod]RhOH] (cod = 1,5-cyclooctadiene) (rate constants 6.7 and 0.5 M\(^{-1}\) s\(^{-1}\) at 50°C).\(^{22}\)

Considering Phbod is considerably more sterically congested than cod, the approximately equal B-to-Rh transfer barriers (10.4 vs. 11.0 kcal mol\(^{-1}\)) for ligands II and I predicted by the computation are not surprising. Structurally, the stationary points are very similar for both ligands (Figure 5b). For the pre-complexed reactants, the O···H-B bond length is 1.583 Å in 23 vs. 1.560 in 5a. Going into the B activation TS, this is replaced by a O-B bond having length of 2.391 Å in 24 and 2.388 Å in 6a; the B-C\(_1\) bonds are 1.585 and 1.590 Å, respectively. In the B-to-Rh transfer TS, the B-C\(_1\) bonds become 2.096 and 2.050 Å, and the Rh-C\(_1\) bonds become 2.205 and 2.188 Å in 26 and 10, respectively.

The favourable energetics for the non-hydrated “in” pathway for both ligands lends a strong first principles support to “Miyaura’s intermediate” (Figure 1a) in the most typical case of Rh-catalyzed 1,4-addition reaction. Recent work by Lan has shown analogous B-to-Rh pathway in their study of the [cod]Rh]-mediated C-Si bond scission reaction.\(^{14}\) Earlier, de Bruin and co-workers performed a computational study of the aldehyde arylation under anhydrous conditions.\(^{15}\) The results obtained herein, which include effect of water co-solvent as well as treatment of the full ligand structures (and not just two PH\(_3\) particles), are in excellent qualitative agreement. On the other hand, the group of Gois computationally demonstrated that in a similar reaction catalyzed by a N-heterocyclic carbene-Rh\(_2\)(OAc)\(_3\) complex, there is no transmetalation; rather, the Rh catalyst assists with boronic acid activation, which then engages in a direct nucleophilic attack on the aldehyde activated by an H-bond.\(^{31}\) Houk et al. found a structure representing the Pd ‘‘Miyaura’s intermediate’’ in their theoretical investigation of the [(bipy)Pd[(OMe)]-mediated 1,4-addition (bipy=2,2’-bipyridyl) to 3-methyl-2-cyclohexenone.\(^{32}\) Whereas no direct experimental support has been provided to date for Rh arylations, Hartwig et al. demonstrated\(^{32}\) that isolated [(Et\(_2\)P)Rh-O-B(Ph)Ar] (R = OH or Ar) underwent B-to-Rh aryl transfer upon heating while producing a boron-containing polymer instead of B(OH)\(_3\); no hypervalent B compounds were detected. Also, kinetic experiments\(^3\) as well as very recent DFT calculations\(^8\) have established the viability of analogous [Ar-Pd(II)-OH] species in Suzuki-Miyaura cross-couplings.

Conclusions

Exploration of the transmetalation of phenylboronic acid to Rh(I)-hydroxide ligated with a chiral bidentate phosphone (binap) and a chiral diene (Phbod) by DFT calculations (IEFPCM/PBE0/DGDZVP level of theory) reveals a two step process comprised of boron activation by the Rh-bonded OH group followed by a B-to-Rh transfer. Whereas the barriers associated with the TSs for both steps were of approximately equal height for Phbod, the first one was much higher for binap. This difference is predominantly entropic in nature. The computations agree well with the experimental findings that transmetalation for [Rh(binap)] is slower than [Rh(Phbod)] and lend first principles support to the “Miyaura’s intermediate” postulated in 2004 to arise from quarternization of the boronic acid by Pd(II) or Rh(I)-bound hydroxide.

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Graphical abstract

DFT study on the transmetalation of PhB(OH)₂ to diphosphane and diene Rh catalysts confirms the proposed intermediate and reactivity trends.