On the Mechanism of Phosphinidene Complex Arylation by Arylboronic acids

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Abstract

The arylation reaction of terminal phosphinidene complexes [RP-W(CO)$_5$] by arylboronic acids is very sensitive to steric hindrance and electronic properties of the substituents on the aryl ring. Based on DFT calculations and additional experiments, it seems that the mechanism involves first an insertion of the phosphinidene into one of the B-O bonds, followed by an intramolecular nucleophilic attack of the aryl group onto the P-OH bond promoted by the potassium phosphate. The [1,2] aryl shift from B to P cannot be reproduced with an alkyl group.

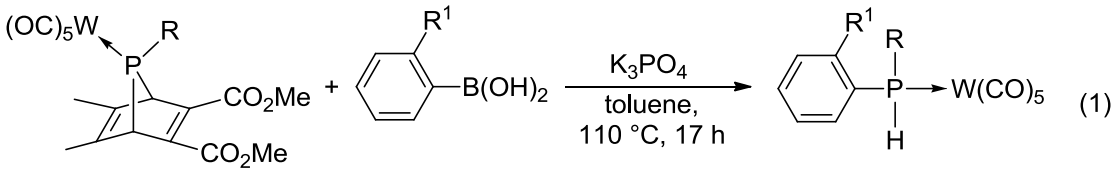
Introduction

The building of phosphorus-carbon bonds is at the core of organophosphorus chemistry[1], exactly as the building of C-C bonds is at the core of organic chemistry. In this context, the development of a new route to P-C bonds involving the reaction of monovalent phosphorus species [RP-W(CO)$_5$] with aryl or heteroaryl-boronic acids[2] is an interesting addition to the existing methodologies, mainly because it uses the wide array of reagents developed for the Suzuki cross-coupling reaction. Unfortunately, at the moment, the mechanism of this P-C coupling is unknown and we cannot explain why the reaction does not work with alkyl groups. In this report we try to shed some light on this question.

Results and Discussion

As a first step, we decided to collect some additional information on the effect of aryl substituents on the yields of the arylation reaction. For this purpose, we first allowed the phenyl and methylphosphinidene precursors of [RP-W(CO)$_5$] to react with a

series of *ortho*-substituted phenylboronic acids in order to check the effect of steric hindrance (eq.1).



(1)

R = Ph **1a**
R = Me **1b**

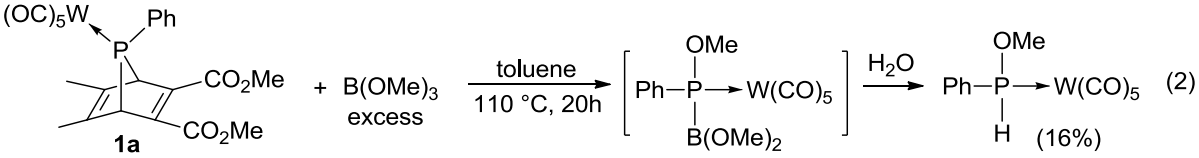
2a R^1 = H
2b R^1 = Me
2c R^1 = Ph
2d R^1 = OEt

3a R = Ph R^1 = H 48%
3b R =Me R^1 = H 46%
3c R = Ph R^1 = Me 9%
3d R = Me R^1 = Me 8%
3e R = Ph R^1 = Ph 0%
3f R = Ph R^1 = OEt 27%
3g R = Me R^1 = OEt 40%

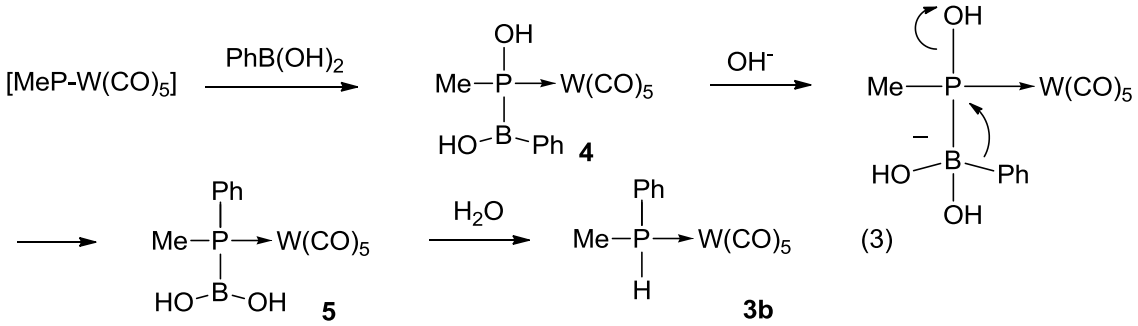
The negative steric effect of *ortho*-substitution is quite clear from these data. The positive electronic effect of the alkoxy group is also quite striking since it almost overcome the negative effect of its steric hindrance. In order to confirm the favorable effect of electron-donating and, symmetrically, the negative effect of electron-withdrawing substituents, we also tested the reaction of some *para*-substituted phenylboronic acids. Both the *para*-CHO and $B(OH)_2$ electron-withdrawing substituents completely block the reaction. We can conclude that the phosphinidene plays its classical electrophilic role[3] whereas the aryl is the nucleophile in this reaction. Surprisingly, the phosphate base does not kill the electrophilicity of the phosphinidene. We confirmed this point by allowing the precursor **1a** to react with diphenylacetylene in the presence of potassium phosphate under the standard conditions. The reaction still produces the phosphirene[4] in 45% yield versus 84% without the phosphate. One of the reasons why the phosphate does not strongly interact with the phosphinidene is, undoubtedly, because most of it stays out of the solution.

A key piece of information arose when we discovered that the reaction of **1a** with **2a** still produces **3a** in the absence of K_3PO_4, although in the much lower yield of 14%. From a theoretical standpoint, this meant that we could start the study of the mechanism by an investigation of the phosphinidene + boronic acid reaction. We chose the [MeP-$W(CO)_5$] + $PhB(OH)_2$ system. The computations were performed using DFT at the B3LYP or RB3PW91 – Lanl2dz (W) levels.[5] We can envisage two types of interaction between the phosphinidene and the boronic acid. In the first one, the phosphinidene plays its usual electrophilic role and interacts with the sp^2 in plane

lone pair of one boronic oxygen by its LUMO. In the other one, the phosphinidene uses its in plane sp^2 lone pair (HOMO) to interact with the vacancy at boron, thus playing the less frequent role of a nucleophile.[6] Even when choosing the second, less likely interaction, the optimization led to the phosphinidene insertion product into the B-O bond (**4**). The reaction is somewhat similar to the classical insertion of phosphinidenes into water.[7] In order to check the likeliness of this reaction, we allowed the precursor **1a** to react with trimethyl borate. The result is shown in eq. (2).



The insertion of the phosphinidene into the B-O bond indeed takes place. The structure of (**4**) is shown in figure (1). At 1.954 Å, the B-P bond is a typical single bond (compare with the B-P bond of H_3B-PPh_3 at 1.917 Å[8]). Boron is planar (Σ angles at B 359.9 deg.). Thus, boron has a vacant p orbital that strongly participate to the LUMO as shown in figure (2). The Ph-P-B-OH isomerisation product (**5**) whose hydrolysis could yield **3b** was also investigated. Its geometry is shown in figure (3). The key point is that (**5**) lies 22.9 kcal mol^{-1} lower in energy than (**4**). Thus, by analogy with the classical mechanism of the Suzuki reaction, we think that the phosphate base coordinates to the boron center of (**4**) and increases the nucleophilicity of the phenyl group. The phenyl group then performs an internal nucleophilic substitution of the P-OH bond to give an analogue of (**5**). The proposed mechanism is depicted using HO^- as the base (eq. 3).



During the shift of the phenyl group from B to P, the *ipso*-carbon becomes tetracoordinate. A similar shift involving an alkyl group would produce a transient pentacoordinate carbon that would be much higher in energy. Thus, it is possible to understand why the P-C bond formation does not work with alkyl groups. For the

same reason, the isomerisation of 1*H* into 2*H*-phospholes works with aryl but not with alkyl groups.[9]

Experimental

All reactions were performed under nitrogen using solvents dried by standard methods. NMR spectra were obtained using Bruker AV400 spectrometer operating at 400 MHz for ^{1}H, 100.64 MHz for ^{13}C, 162.02 MHz for ^{31}P. Spectra were recorded at 298 K in CD_2Cl_2. All coupling constants (*J* values) are reported in Hertz (Hz). HRMS spectra were obtained on a Water Q–Tof Premier MS. Silica gel (230–400 mesh) was used for the chromatographic separations. 7-Phosphanorbornadiene complexes were prepared as indicated in the literature.[10] Commercially available arylboronic acids were dried with the Dean-Stark technique prior to use.

General procedure for the synthesis of ***3c,d,f,g***

Toluene (3 mL) was added to a mixture of 7-phosphanorbornadiene complex (0.3 mmol.), arylboronic acid (0.9 mmol.) and anhydrous K_3PO_4 (1.2 mmol.) in a pressure tube under nitrogen. The tube was sealed and heated at 110 °C for 17-24 h. Solvent was evaporated and the residue was strained onto silica. Purification was performed via cold column chromatography (0 °C) with 15:1 hexane-dichloromethane.

3c: White solid (14 mg, 9% yield) was obtained. ^{31}P NMR (CD_2Cl_2): δ -27.4 ($^{1}J_{PW}$ = 228.2 Hz, $^{1}J_{PH}$ = 348.1 Hz). ^{1}H NMR (CD_2Cl_2): δ 2.37 (s, 3H, Me), 7.03 (d, $^{1}J_{PH}$ = 348.1 Hz, 1H, PH), 7.25-7.62 (m, 9H, Ar). ^{13}C NMR (CD_2Cl_2): δ 21.55 (d, $^{3}J_{CP}$ = 6.5 Hz, CH_3), 126.95 (d, J_{CP} = 11.5 Hz, CH), 129.47 (d, J_{CP} = 10.2 Hz, CH), 131.06 (d, J_{CP} = 2.1 Hz, CH), 131.27 (d, J_{CP} = 1.9 Hz, CH), 131.29 (d, $^{1}J_{CP}$ = 43.6 Hz, CP), 131.65 (d, J_{CP} = 6.8 Hz, CH), 131.76 (d, $^{1}J_{CP}$ = 42.9 Hz, CP), 133.51 (d, J_{CP} = 12.0 Hz, CH), 133.89 (d, J_{CP} = 16.7 Hz, CH), 140.11 (d, $^{2}J_{CP}$ = 5.7 Hz, C-Me), 196.81 (d, $^{2}J_{CP}$ = 6.9 Hz, cis CO), 199.65 (d, $^{2}J_{CP}$ = 21.5 Hz, trans CO). HRMS: m/z 524.0015 (calcd for $C_{18}H_{13}O_5PW$ 524.0010).

3d: White solid (13 mg, 8% yield) was obtained. ^{31}P NMR (CD_2Cl_2): δ -60.1 ($^{1}J_{PW}$ = 222.2 Hz, $^{1}J_{PH}$ = 345.5 Hz). ^{1}H NMR (CD_2Cl_2): δ 2.01 (dd, $^{2}J_{PH}$ = 8.0 Hz, $^{3}J_{HH}$ = 6.6 Hz, 3H, CH_3), 2.49 (s, 3H, CH_3), 6.03 (dq, $^{1}J_{PH}$ = 345.5 Hz, $^{3}J_{HH}$ = 6.6 Hz, 1H, PH), 7.26-7.45 (m, 4H, Ar). ^{13}C NMR (CD_2Cl_2): δ 13.43 (d, $^{1}J_{CP}$ = 29.9 Hz, P-Me), 21.03 (d, $^{3}J_{CP}$ = 7.2 Hz, Me), 126.97 (d, J_{CP} = 10.2 Hz, CH), 130.56 (d, J_{CP} = 2.0 Hz, CH),

130.58 (d, J_{CP} = 29.5 Hz, CH), 131.30 (d, J_{CP} = 6.9 Hz, CH), 132.87 (d, $^{1}J_{CP}$ = 43.3 Hz, CP), 139.15 (d, $^{2}J_{CP}$ = 6.8 Hz, C-Me), 196.90 (d, $^{2}J_{CP}$ = 7.0 Hz, cis CO), 200.01 (d, $^{2}J_{CP}$ = 20.3 Hz, trans CO). HRMS: m/z m/z 461.9877 (calcd for $C_{13}H_{11}O_5PW$ 461.9854).

3f: White solid (46 mg, 27% yield) was obtained. ^{31}P NMR (CD_2Cl_2): δ -30.6 ($^{1}J_{PW}$ = 227.7 Hz, $^{1}J_{PH}$ = 356.7 Hz). ^{1}H NMR (CD_2Cl_2): δ 1.36 (pseudo-td, $^{3}J_{HH}$ = 6.8 Hz, J_{HH} = 2.0 Hz, 3H, $C\underline{H}_3CH_2O$), 4.07 (m, 2H, $CH_3C\underline{H}_2O$), 6.94 (pseudo-dd, $^{1}J_{PH}$ = 356.7 Hz, J_{HH} = 2.5 Hz, 1H, PH), 6.92-7.71 (m, 9H, Ar). ^{13}C NMR (CD_2Cl_2): δ 14.62 (s, $\underline{C}H_3CH_2O$), 64.49 (s, $CH_3\underline{C}H_2O$), 111.76 (d, J_{CP} = 4.0 Hz, CH), 120.91 (d, $^{1}J_{CP}$ = 44.5 Hz, CP), 121.22 (d, J_{CP} = 9.6 Hz, CH), 129.14 (d, J_{CP} = 10.2 Hz, CH), 130.92 (d, J_{CP} = 1.6 Hz, CH), 131.25 (d, $^{1}J_{CP}$ = 44.4 Hz, CP), 132.77 (s, CH), 133.19 (d, J_{CP} = 8.8 Hz, CH), 133.98 (d, J_{CP} = 11.9 Hz, CH), 159.09 (d, $^{2}J_{CP}$ = 3.2 Hz, $\underline{C}OCH_2$), 197.10 (d, $^{2}J_{CP}$ = 7.0 Hz, cis CO), 200.17 (d, $^{2}J_{CP}$ = 21.4 Hz, trans CO). HRMS: m/z 554.0119 (calcd for $C_{19}H_{15}O_6PW$ 554.0116).

3g: White solid (80 mg, 40% yield) was obtained. ^{31}P NMR (CD_2Cl_2): δ -57.3 ($^{1}J_{PW}$ = 223.8 Hz, $^{1}J_{PH}$ = 350.2 Hz). ^{1}H NMR (CD_2Cl_2): δ 1.50 (t, $^{3}J_{HH}$ = 6.9 Hz, 3H, $C\underline{H}_3CH_2O$), 2.00 (pseudo t, $^{2}J_{PH}$ = 6.9 Hz, 3H, CH_3), 4.14 (m, 2H, $CH_3C\underline{H}_2O$), 5.95 (dq, $^{1}J_{PH}$ = 350.2 Hz, $^{3}J_{HH}$ = 6.5 Hz, 1H, PH), 6.93-7.43 (m, 4H, Ar). ^{13}C NMR (CD_2Cl_2): δ 12.41 (d, $^{1}J_{CP}$ = 29.9 Hz, P-Me), 14.78 (s, $\underline{C}H_3CH_2O$), 64.41 (s, $CH_3\underline{C}H_2O$), 111.54 (d, J_{CP} = 4.4 Hz, CH), 121.02 (d, $^{1}J_{CP}$ = 45.7 Hz, Ar CP), 121.15 (d, J_{CP} = 9.1 Hz, CH), 131.48 (d, J_{CP} = 6.6 Hz, CH), 132.44 (d, J_{CP} = 1.1 Hz, CH), 159.48 (d, $^{2}J_{CP}$ = 4.0 Hz, $\underline{C}OCH_2$), 197.22 (d, $^{2}J_{CP}$ = 7.2 Hz, cis CO), 200.17 (d, $^{2}J_{CP}$ = 20.3 Hz, trans CO). HRMS: m/z 491.9948 (calcd for $C_{14}H_{13}O_6PW$ 491.9959).

*Synthesis of **3a** without potassium phosphate*

Toluene (3 mL) was added to a mixture of 7-phosphanorbornadiene complex **1a** (200 mg, 0.3 mmol.), phenylboronic acid (187 mg, 1.5 mmol.) in a pressure tube under nitrogen. The tube was sealed and heated at 110 °C for 18 h. Solvent was evaporated and the residue was strained onto silica. Purification was performed via cold column chromatography (0 °C) with 15:1 hexane-dichloromethane. **3a** was obtained as a white solid (22 mg, 14%).

*Reaction of **1a** with trimethyl borate*

Excess $B(OMe)_3$ (1 mL) was added to a toluene solution (2 mL) of phosphanorbornadiene complex **1a** (200 mg, 0.3 mmol.) in a pressure tube under nitrogen. The mixture was heated with stirring at 110 °C for 20 h. Solvent was evaporated and the residue was strained onto silica. Purification was performed via cold column chromatography (0 °C) with 15:1 hexane-dichloromethane. Yield of the (methoxy)phenylphosphine complex was 16%. Reaction was repeated in the presence of dry potassium phosphate (260 mg, 1.2 mmol.) and the yield was 20%.

Synthesis of the 1,2,3-triphenylphosphirene complex

Toluene (3 mL) was added to a mixture of 7-phenylphosphanorbornadiene complex **1a** (200 mg, 0.3 mmol.) and diphenylacetylene (220 mg, 1.2 mmol.) in a pressure tube. The tube was sealed and heated at 110 °C for 21 h. Solvent was evaporated and the residue was strained onto silica. Purification was performed via cold column chromatography (0 °C) with 15:1 hexane-dichloromethane. Yield was 84%. Reaction was repeated in the presence of dry potassium phosphate (260 mg, 1.2 mmol.) and the yield was 45%.

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Supporting Information Available: NMR spectra for compounds **3c**, **3d**, **3f** and **3g** This material is available free of charge via the Internet at http://pubs.acs.org.

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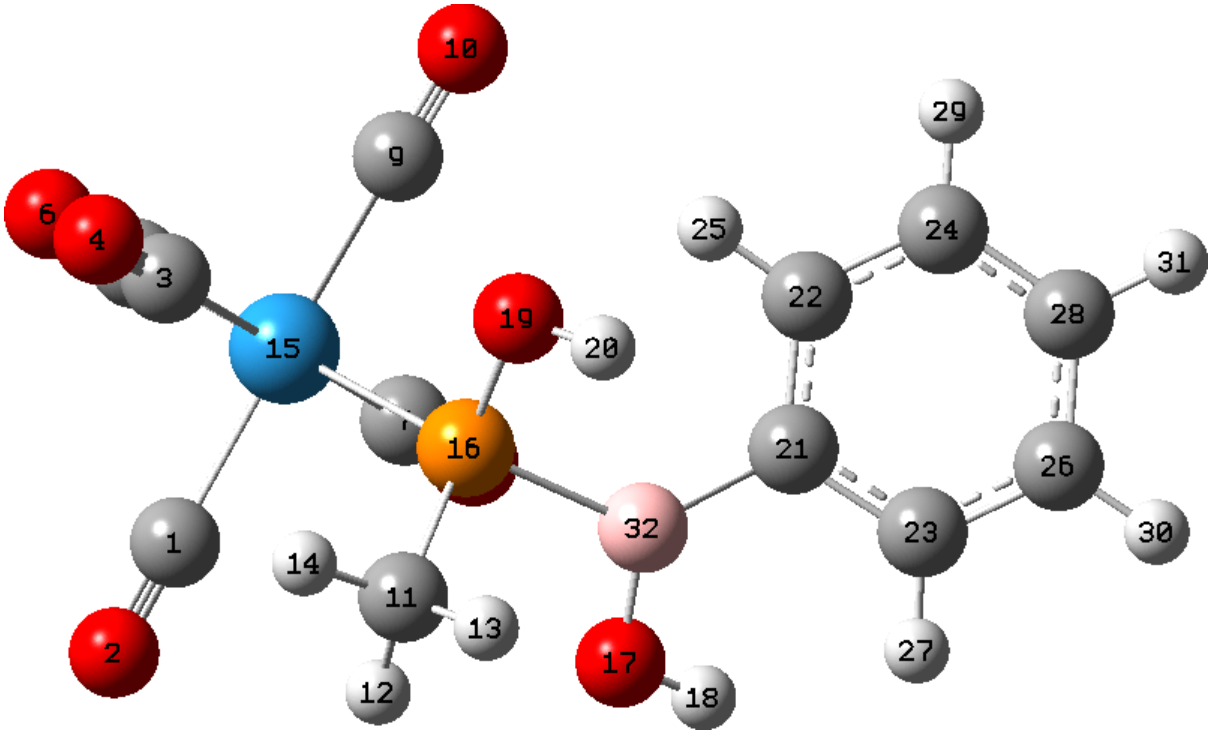


Figure 1: Computed structure of the phosphinidene insertion product (**4**). Main distances (Å) and angles (deg.): P16-B32 1.954, P16-W15 2.504, P16-O19 1.668, P16-C11 1.842, B32-O17 1.359, B32-C21 1.557; W15-P16-B32 115.0, W15-P16-O19 110.5, W15-P16-C11 116.8, B32-P16-O19 106.7, P16-B32-O17 111.9, P16-B32-C21 124.9, O17-B32-C21 123.1; O19-P16-B32-C21 20.3.

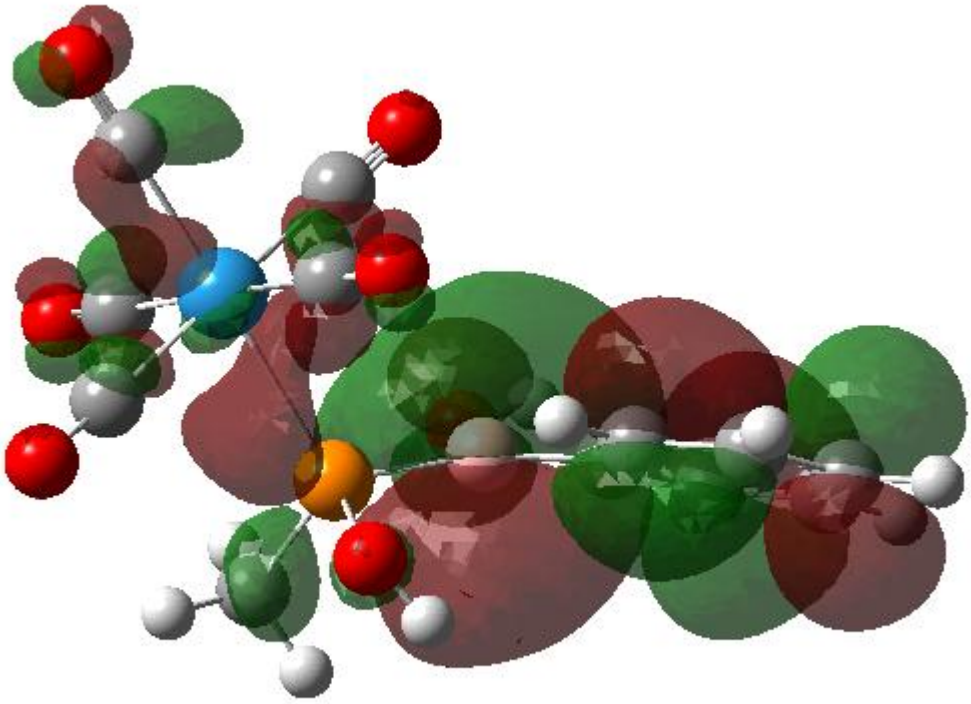


Figure 2: LUMO (Kohn-Sham) of insertion product (**4**).

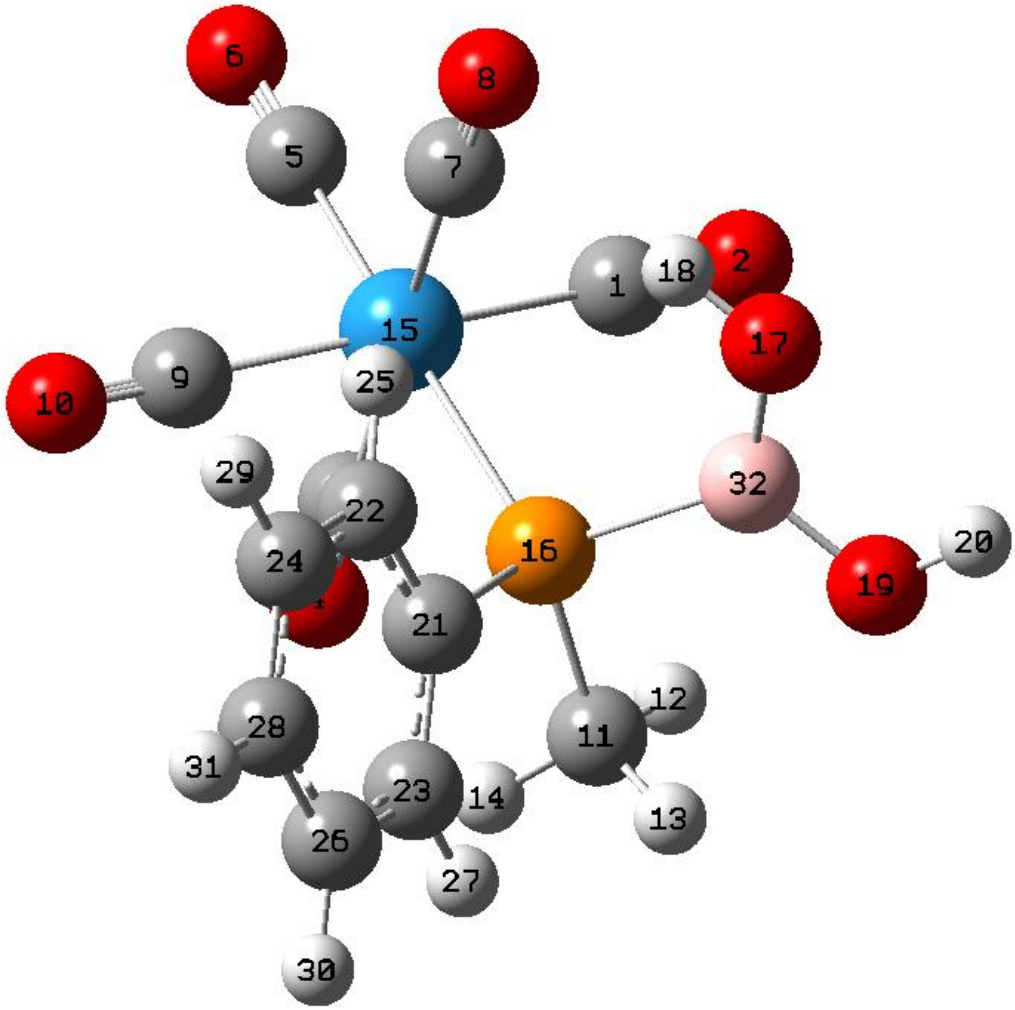
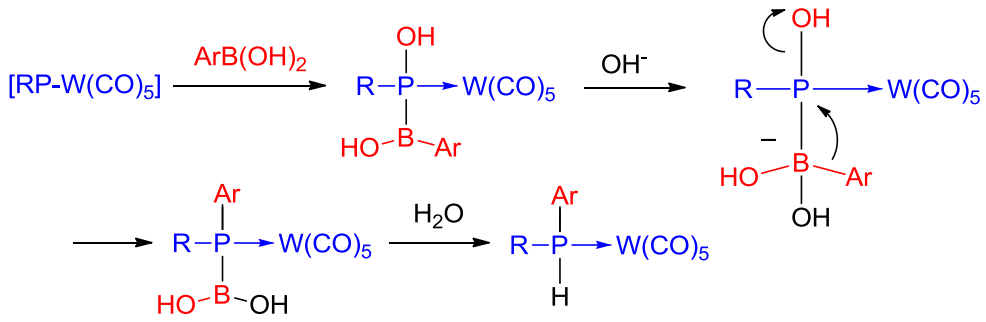


Figure 3: Computed structure of the isomerisation product (**5**). Main distances (Å) and angles (deg.): P16-B32 1.964, P16-W15 2.556, P16-C21 1.844, P16-C11 1.843, B32-O17 1.358, B32-O19 1.358; W15-P16-B32 114.1, W15-P16-C21 117.0, W15-P16-C11 115.0, B32-P16-C21 101.2, P16-B32-O17 123.9, P16-B32-O19 116.4, O17-B32-O19 119.7; C21-P16-B32-O19 103.2.

Graphical Abstract



Terminal phosphinidene complexes react with arylboronic acid by a two-step mechanism starting by an insertion of P into the B-O bond.