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PALLADIUM(0)-MEDIATED C–S AND O–H BONDS CLEAVAGE REACTION IN 2-HYDROXYBENZYL PHENYL SULFIDE: FORMATIONS OF OXYPHOSPHORANE AND 1,2-OXAPALLADACYCLE

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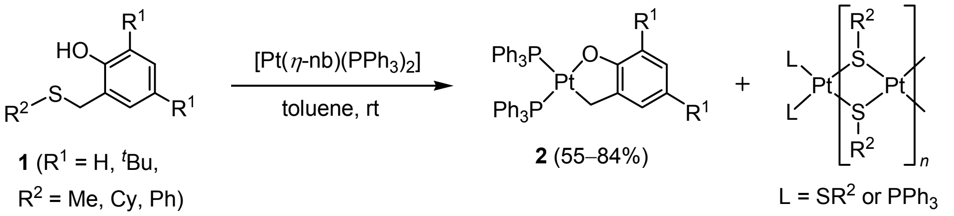
‡This paper is dedicated to Professor Isao Kuwajima on the occasion of his 77th birthday.

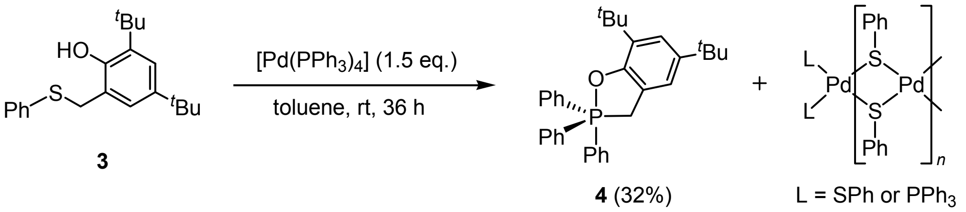
Abstract – Treatment of 2-hydroxybenzyl phenyl sulfide **3** with 1.5 equiv. of [$Pd(PPh_3)_4$] in toluene led to the unanticipated formation of oxyphosphorane **4** in 30% isolated yield. In contrast, the reaction of **3** with Pd(0) complex bearing PMe_3 ligands in toluene afforded the corresponding 1,2-oxapalladacycle **7** and oxyphosphorane **9** in addition to dithiolato complex *trans*-[$Pd(SPh)_2(PMe_3)_2$] **8**.

Oxametallacycles have received remarkable attention in past years because of their unique structures and behaviors as key intermediates in catalytic reactions.[1] In particular, reactions involving oxapalladacycles have proved to be useful for the synthesis of various types of organic compounds and heterocycles.[2,3] For example, Malinakova and co-workers have demonstrated the synthesis of a series of five-membered 1,3-oxapalladacycles featuring a Pd-bonded sp^3-hybridized stereogenic carbon and phosphine or *N*,*N*-chelating ligands.[4] The stoichiometric reactions of these oxapalladacycles with alkynes or allenes efficiently afforded 2*H*-1-benzopyrans.[4] However, investigations of five-membered 1,2-oxapalladacycles with a Pd–O bond were quite limited probably due to a lack of suitable synthetic methods.[5] Meanwhile, we have recently found the Pt(0)-promoted $C(sp^3)$–S and O–H bonds cleavages of 2-hydroxybenzyl sulfide derivatives (**1**) to lead to an unexpected formation of novel five-membered 1,2-oxaplatinacycles (**2**) (Scheme 1).[6] In this contribution, we present the sequential bond cleavage reaction of 2-hydroxybenzyl phenyl sulfide with Pd(0) complexes.



Scheme 1. Reaction of 2-hydroxybenzyl sulfide derivatives **1** with Pt(0) complex

When 2-hydroxybenzyl phenyl sulfide **3** was allowed to react with 1.5 equiv. of $[Pd(PPh_3)_4]$ in toluene at room temperature for 36 h, the five-coordinated phosphine compound, oxyphosphorane **4**, instead of the expected corresponding five-membered 1,2-oxapalladacycle, was produced in 30% isolated yield together with polymeric palladium clusters as insoluble materials (Scheme 2).[7] The molecular structure of **4** was characterized by ^{1}H, $^{13}C\{^{1}H\}$, and $^{31}P\{^{1}H\}$ NMR spectroscopy, and finally verified by X-ray crystallographic analysis. In the ^{1}H NMR of **4**, the characteristic benzylic protons were observed as a doublet signal at δ 2.77 with the ^{1}H-^{31}P coupling constant of 13 Hz. In the $^{31}P\{^{1}H\}$ NMR spectrum of **4**, a sharp singlet appeared at δ –41.5, which is comparable to those of the reported oxyphosphoranes (δ –60.8 to –39.8).[8]



Scheme 2. Reaction of **3** with $[Pd(PPh_3)_4]$

Colorless single crystals of **4** suitable for X-ray crystallography were grown from a concentrated CH_2Cl_2/hexane solution at −18 °C. As illustrated in Figure 1,[9] the phosphorus center adopts a slightly distorted trigonal bipyramidal geometry that has a phenoxide oxygen (O1) and a phenyl carbon (C4) atoms at apical positions and a benzylic carbon (C1) and two phenyl carbons at equatorial positions. The P–O bond length is 1.8738(17) Å, which is slightly elongated in comparison with those of the previously reported oxyphosphoranes within the range of 1.75 to 1.85 Å.[8] As expected,[10] three equatorial P–C bonds [1.816(2)–1.841(2) Å] are remarkably shorter than the apical P1–C4 bond [1.912(2) Å].

The formation mechanism of **4** is reasonably explained as shown in Scheme 3. In the first stage, the C–S and O–H bonds cleavage of **3** mediated by Pd(0) complex would occur to furnish the corresponding 1,2-oxapalladacycle **5** as an initial intermediate similarly to the formation of 1,2-oxaplatinacycle **2**.[6] Then, nucleophilic attack of the phenoxide oxygen in **5** at the coordinated *cis* phosphorus center takes place to give a six-membered palladaphosphorane intermediate **6**.[11] Finally, the coordination of PPh_3 to the palladium center in **6** followed by the reductive elimination of [Pd(PPh_3)$_2$] or direct elimination of Pd(0) species from **6** leads to the formation of **4**.

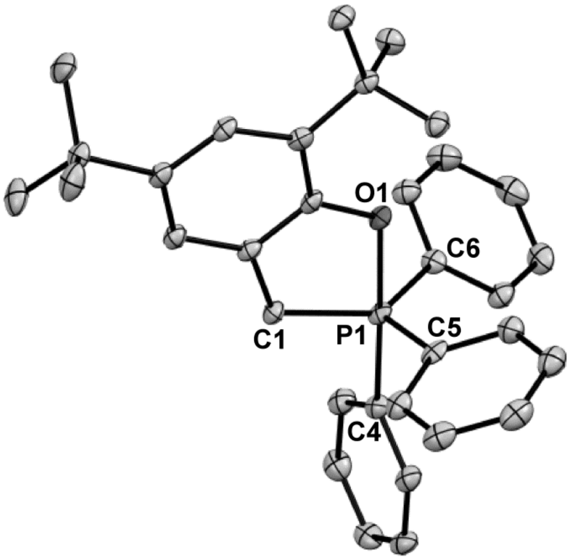
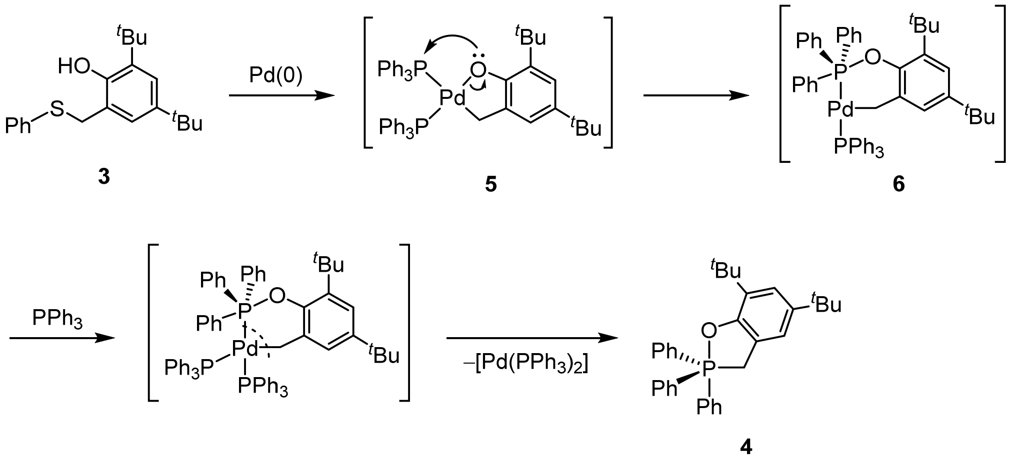


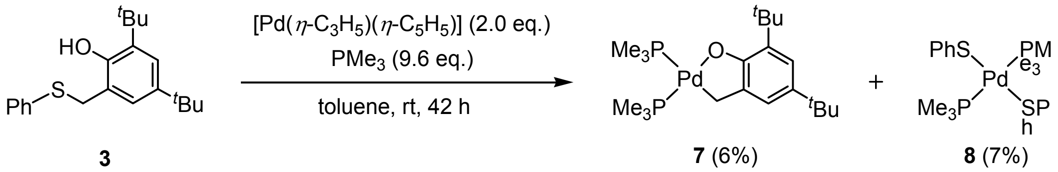
Figure 1. ORTEP diagram of **4** with 50% thermal ellipsoids. All hydrogen atoms are omitted for clarity. Selected bond lengths [Å] and angles [°]: P1–O1 1.8738(17), P1–C1 1.841(2), P1–C4 1.912(2), P1–C5 1.816(2), P1–C6 1.832(2), O1–P1–O2 102.33(6), O1–P1–C4 175.35(11), O1–P1–C1 86.74(9), C1–P1–C4 92.33(11), C1–P1–C5 115.63(11), C1–P1–C6 125.10(11), C5–P1–C6 118.04(11).



Scheme 3. Plausible formation mechanism for **4**

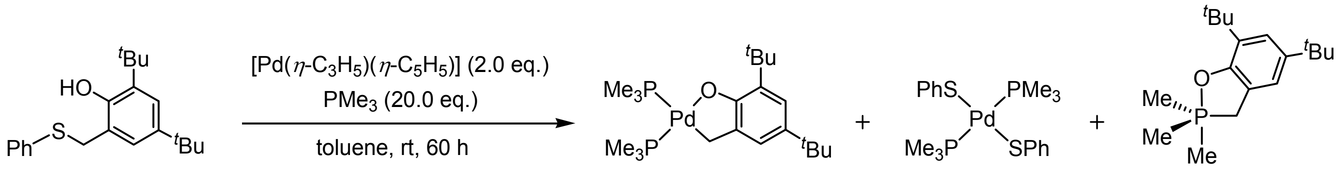
We next carried out the reaction of **3** with Pd(0) complex bearing much strong σ-donor PMe_3 ligands. Treatment of **3** with [Pd(PMe_3)$_4$] in toluene at room temperature for 42 h, which is generated in situ by the reaction of 2.0 equiv. of [Pd(η-C_3H_5)(η-C_5H_5)] with 9.6 equiv. of PMe_3, afforded a mixture of 1,2-oxapalladacycle **7** and dithiolato complex *trans*-[Pd(SPh)$_2$(PMe_3)$_2$] **8**[5b] in the ratio of 1.6:1.0 based on the $^{31}P\{^1H\}$ NMR integral ratio (Scheme 4). After rinsing with Et_2O and hexane, **7** and **8** were isolated in

6% and 7% yields, respectively.[12] In the ^{1}H NMR spectrum of **7**, a characteristic doublet of doublets signal due to benzylic protons was observed at δ 3.16 with the ^{31}P coupling constants of 9 and 5 Hz, and two methyl protons for PMe_3 ligands appeared at δ 0.72 ($^3J_{P-H}$ = 10 Hz) and 1.01 ($^3J_{P-H}$ = 7 Hz) as doublet signals. The $^{31}P\{^1H\}$ NMR spectrum of **7** displayed two nonequivalent doublet signals with ^{31}P coupling constant of 35 Hz at δ −19.3 and −8.7. The molecular structure of **7** was supported by the X-ray diffraction, but we are not able to discuss any structural parameters owing to the low quality of crystal data.[13]



Scheme 4. Reaction of **3** with $[Pd(\eta\text{-}C_3H_5)(\eta\text{-}C_5H_5)]$ in the presence of PMe_3

In relation to the formation mechanism for **4**, we examined the reaction of **3** with $[Pd(\eta\text{-}C_3H_5)(\eta\text{-}C_5H_5)]$ in the presence of an excess amount of PMe_3 (20 eq.) in toluene for 60 h. As the result, the corresponding trimethyl-substituted oxyphosphorane **9** together with complexes **7** and **8** were mainly produced in the ratio of 0.2:1.0:0.1 judged by the $^{31}P\{^1H\}$ NMR (Scheme 5).[14] In the ^{1}H NMR of **9**, the benzylic protons were exhibited as a doublet signal at δ 2.47 ($^3J_{P-H}$ = 14 Hz), which is somewhat high-field shifted compared with that of the above mentioned **4**. The three methyl protons in **9** were observed equivalently as a doublet signal at δ 0.97 ($^3J_{P-H}$ = 11 Hz) due to Berry pseudorotation in the NMR time scale.[10,15] The $^{31}P\{^1H\}$ NMR spectrum of **9** showed a broad singlet at δ −53.3. The formation of **9** suggests that the coordination of free phosphine to the palladium center of palladaphosphorane intermediates like **6** induces the reductive elimination of Pd(0) species to give oxyphosphoranes **4** and **9**.



Scheme 5. Reaction of **3** with $[Pd(\eta\text{-}C_3H_5)(\eta\text{-}C_5H_5)]$ in the presence of an excess amount of PMe_3

In summary, we have demonstrated the unique reactivity of 2-hydroxybenzyl phenyl sulfide **3** with Pd(0) complexes via unusual $C(sp^3)$–S and O–H bonds cleavage giving the novel oxyphosphoranes **4** and **9** or 1,2-palladacycle **7**. Further investigations on the bond cleavage of **3** are currently in progress using other transition metal complexes.

ACKNOWLEDGEMENTS

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7. A solution of **3** (90.2 mg, 0.28 mmol) in toluene (6 mL) was added to a solution of [Pd(PPh_3)$_4$] (501.0 mg, 0.43 mmol) in toluene (15 mL) at room temperature. The mixture was stirred for 36 h at room temperature, and then the solvent was removed under reduced pressure. The residue was dissolved in a mixed solvent of hexane and CH_2Cl_2, and insoluble PPh_3=O and palladium black were removed by filtration. The filtrate was evaporated to dryness and the residue was washed with MeOH to give oxyphosphorane **4** (39.9 mg, 32%) as colorless crystals. **4**: Mp 155–156 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.98 (s, 9 H), 1.29 (s, 9 H), 3.75 (d, $^2J_{P-H}$ = 13 Hz, 2 H), 7.01 (s, 1 H), 7.09 (s,

1 H), 7.23–7.35 (m, 15 H); $^{13}C\{^{1}H\}$ NMR (101 MHz, $CDCl_3$) δ 28.9 (CH_3), 31.9 (CH_3), 33.5 (d, $^{1}J_{P-C}$ = 96 Hz, CH_2), 34.18 (C), 34.23 (C), 118.7 (C), 118.8 (d, $^{3}J_{P-C}$ = 19 Hz, CH), 121.6 (CH), 127.5 (d, $^{2}J_{P-C}$ = 17 Hz, CH), 128.5 (d, $^{4}J_{P-C}$ = 2 Hz, CH), 131.0 (d, $^{3}J_{P-C}$ = 9 Hz, CH), 132.7 (d, $^{2}J_{P-C}$ = 10 Hz, C), 132.3 (C), 137.5 (C), 154.2 (d, $^{2}J_{P-C}$ = 4 Hz, C–O); $^{31}P\{^{1}H\}$ NMR (202 MHz, $CDCl_3$) δ –41.5. HRMS (ESI-TOF) Calcd for $[C_{33}H_{36}OP + H]^{+}$: 481.26548. Found: 481.26565.

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9. Crystallographic data for **4**: $C_{33}H_{37}OP$, MW = 480.60, monoclinic, space group $P2_1/n$, a = 11.731(3) Å, b = 9.649(2) Å, c = 23.473(6) Å, β = 90.344(6)°, V = 2656.9(3) Å^3, Z = 4, D_{calc} = 1.201 g cm^{-3}, R_1 ($I > 2\sigma I$) = 0.0561, wR_2 (all data) = 0.1566 for 4898 reflections and 322 parameters, GOF = 1.067. Deposition number CCDC-1010106 for **4**. Free copies of the data can be obtained via http://www.ccdc.cam.ac.uk/conts/retrieving.html (or from the Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge, CB2 1EZ, UK; Fax: +44 1223 336033; e-mail: deposit@ccdc.cam.ac.uk).
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12. **7**: ^{1}H NMR (300 MHz, C_6D_6) δ 0.70 (d, $^{2}J_{P-H}$ = 10 Hz, 9 H), 1.00 (d, $^{2}J_{P-H}$ = 7 Hz, 9 H), 1.58 (s, 9 H), 1.92 (s, 9 H), 3.17 (dd, $^{3}J_{P-H}$ = 9, 5 Hz, 2 H), 7.31 (s, 1 H), 7.46 (s, 1 H); $^{31}P\{^{1}H\}$ NMR (202 MHz, C_6D_6) δ –19.3 (d, $^{2}J_{P-P}$ = 35 Hz), –8.7 (d, $^{2}J_{P-P}$ = 35 Hz).
13. Crystallographic data for **7**: $C_{21}H_{40}OP_2Pd$, MW = 476.87, monoclinic, space group $P2/n$, a = 21.033(5) Å, b = 12.483(3) Å, c = 21.142(5) Å, β = 93.703(4)°, V = 5539(2) Å^3, Z = 8, D_{calc} = 1.144 g cm^{-3}, R_1 ($I > 2\sigma I$) = 0.1677, wR_2 (all data) = 0.4129 for 32940 reflections and 12673 parameters, GOF = 1.055.
14. **9**: ^{1}H NMR (400 MHz, C_6D_6) δ 0.98 (d, $^{2}J_{P-H}$ = 11 Hz, 9 H), 1.47 (s, 9 H), 1.66 (s, 9 H), 2.48 (d, $^{2}J_{P-H}$ = 13 Hz, 2 H), 7.15 (d, $^{4}J_{H-H}$ = 2 Hz, 1 H), 7.43 (d, $^{4}J_{H-H}$ = 2 Hz, 1 H); $^{13}C\{^{1}H\}$ NMR (101 MHz, C_6D_6) δ 22.4 (d, $^{1}J_{P-C}$ = 75 Hz, PCH_3), 29.8 (CH_3), 32.0 (d, $^{1}J_{P-C}$ = 96 Hz, CH_2), 34.2 (CH_3), 34.5 (C), 35.1 (C), 119.0 (C), 119.6 (CH), 121.8 (CH), 132.4 (C), 136.3 (C), 156.6 (d, $^{2}J_{P-C}$ = 3 Hz, C–O); $^{31}P\{^{1}H\}$ NMR (202 MHz, C_6D_6) δ –56.2.
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