

Studies of reactions of *o*-xylylene- α,α' -dihalides with palladium complexes and the catalytic synthesis of 3-isochromanone

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Abstract

Homogeneous catalysis by palladium complexes with phosphorus(III) ligands of the carbonylation of *o*-xylylene dihalides in the presence of water to form 3-isochromanone has been studied. Triphenylphosphine was found to provide the most effective catalyst, and by-products and intermediates of systems containing this ligand have been investigated. 2-Indanone is one by-product but is unstable to decomposition under catalytic conditions. Excess PPh₃ is necessary to prolong activity of the catalyst but is also transformed to bis-phosphonium compound [*o*-C₆H₄(CH₂PPh₃)₂]₂X₂ (X = Cl or Br); this quaternization has been investigated and the structure of the bromide salt determined by X-ray diffraction. An unstable oxidative addition product of Pd(PPh₃)₄ was detected as a probable intermediate and related to the previously reported but catalytically-inactive complex *trans*-Pd(*o*-CH₂C₆H₄CH₂Cl)Cl(PMe₃)₂, which has been structurally characterized by X-ray diffraction in this work.

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1. Introduction

3-Isochromanone (1,4-dihydro-3*H*-2-benzopyran-3-one) **1**, and its substituted derivatives, are important synthetic intermediates for products of the pharmaceutical and agrochemical industries, as reported in a number of recent patents [1–6]. Compound **1** and derivatives can be synthesized in various ways using sequences of ‘classical’ organic transformations from available precursors [2,7]. However, the most convenient procedures involve metal-catalyzed carbonylations of *o*-substituted benzene derivatives. Thus, Stille reported the synthesis of **1** in 71% yield by palladium-catalyzed carbonylation of *o*-bromomethylbenzyl alcohol [8] and this yield can be significantly improved using modified conditions and Pd(PPh₃)₄ as catalyst [9].

A similar catalytic carbonylation of *o*-benzenedimethanol in the presence of HI(aq) affords **1** in 88% yield (56% isolated) [10]. Catalytic insertion of CO into the cyclic ether phthalan has also been reported [6], and carbonylations of 2-(1-alkynyl)benzenemethanols under higher pressures and temperatures are catalyzed by Rh₄(CO)₁₆ to afford 4-substituted 3-isochromanones [11]. For commercial processes, more convenient starting materials are *o*-xylylene- α,α' -dihalides, **2**, in particular the dichloride which is readily obtained by radical chlorination of *o*-xylene, and recent patents [1,3,4] give experimental details for the Pd-catalyzed conversion of these substrates to **1** in up to 91% yield [1a], with high turnover numbers of >4 K being recorded under some conditions [3].

Homogeneous Pd-catalysts for transformation of **2** to **1** are reported to operate efficiently at loadings of around 0.3 mol% and can be introduced as Pd(II), with procedures described for PdCl₂, Na₂PdCl₄, ‘H₂PdCl₄’ (PdCl₂/HCl) or

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$\text{PdCl}_2(\text{PPh}_3)_2$ [1,3,4], or as the Pd(0) species $\text{Pd}(\text{PPh}_3)_4$ but with lower reported yields for the latter [1b,4]; supported catalysts, including Pd/C, Pd/ CaCO_3 and Pd on Montmorillonite, are also reported [1]. With the exception of PdCl_2 in *N*-methylpyrrolidone (NMP) operating at higher CO pressure and temperature [3], all successful described procedures require the presence of triphenylphosphine (ratio $\text{PPh}_3:\text{Pd} \geq 2.2:1$) and, although alternative phosphines are claimed in patents, no specific examples are given. Water is required as a reagent and reported processes involve two phase aqueous/organic systems; a satisfactory organic solvent is a tertiary alcohol (*t*-butyl or *t*-amyl alcohol) but other solvents such as toluene, xylene or a higher ether may be used; *N,N*-dimethylformamide (DMF) or NMP are also suitable; phase transfer agents can be added but with negligible improvements in reported yields. It is necessary to remove hydrogen halide during the reaction: a base (B) is normally added and this may be inorganic {e.g., $\text{Ca}(\text{OH})_2$ or KHCO_3 } or a hindered amine {e.g., NEtPr_2^i } but the solvent fulfils this role for reactions carried out in NMP or DMF. Reaction conditions are mild: CO pressures of 0.1–0.4 MPa and temperatures of 70–80 °C are required for most systems described [1,3,4], although temperatures of 130–150 °C and CO pressures of 2–4 MPa were specified for reactions in NMP and DMF [3]. A plausible general mechanism is depicted in Scheme 1.

Although the Pd-catalyzed syntheses of **1** run satisfactorily giving consistent yields of >80%, by-products are also formed, including tarry residues. In this work, investiga-

tions of reactions involving palladium–phosphine complexes with *o*-xylylene- α,α' -dihalides are reported in an attempt to throw more light on the mechanism and side reactions of lactone formation.

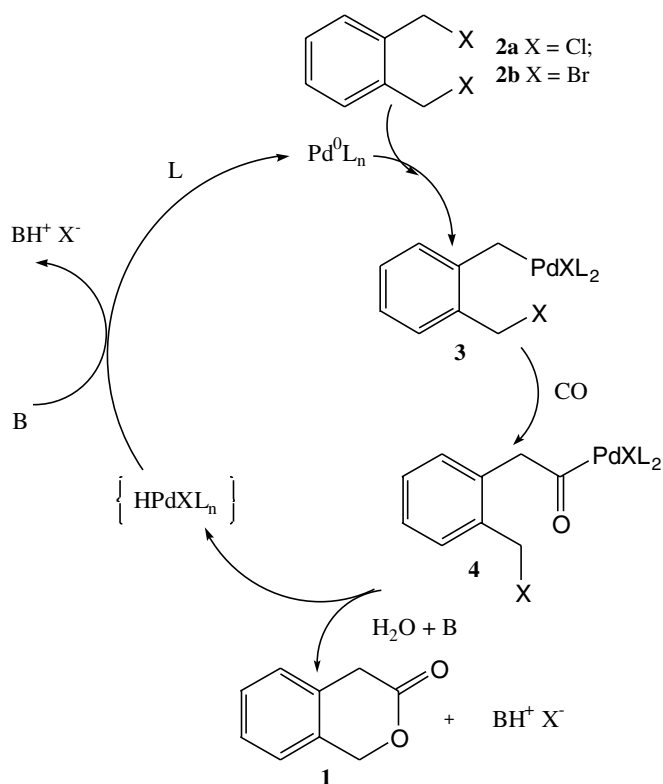
2. Results and discussion

2.1. Studies of palladium-catalyzed formation of 3-isochromanone from *o*-xylylene- α,α' -dihalides

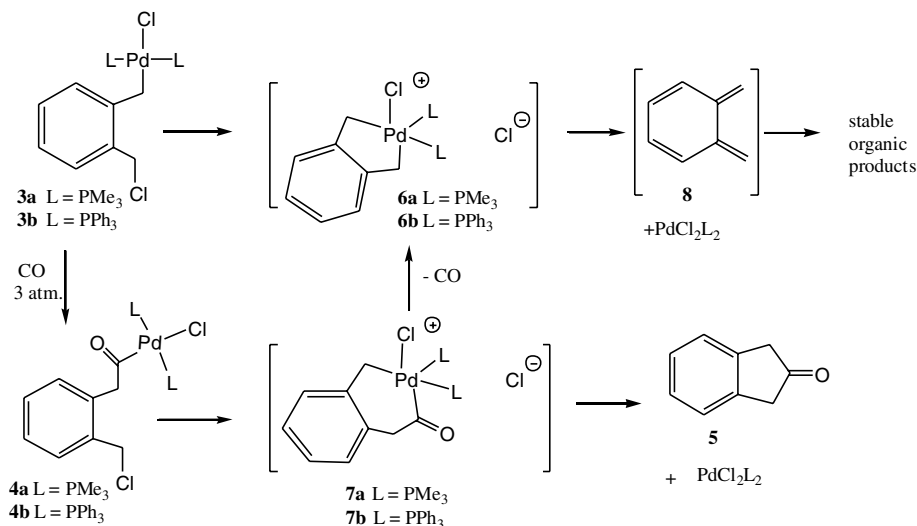
Adopting procedures reported in Ref. [1c], *o*-xylylene- α,α' -dichloride **2a** reacted completely with CO (1 atm) within 45–60 min at 70 °C in the presence of a triphenylphosphine-Pd catalyst (0.2 mol% Pd), yielding 3-isochromanone **1** in >80% yield. A convenient method to prepare the catalyst is to react excess PPh_3 with a Pd(II) compound, such as Na_2PdCl_4 , in a water/*t*-alcohol medium. An excess of phosphine ligand is necessary to prevent loss of catalytic activity which can be partly ascribed to the formation of catalytically-inactive triphenylphosphine oxide in a side-reaction during the course of the carbonylation; a P:Pd molar ratio of ca. 20:1 was found experimentally to be suitable (cf. [1c]). To assess the efficacy of alternative phosphorus(III) ligands in this reaction, potential catalysts were formed as yellow solutions or suspensions by premixing an aqueous solution of Na_2PdCl_4 with an excess of ligand (ligand:Pd ratio 20:1); phosphines PMe_3 , PEt_3 , $\text{P}(\text{C}_6\text{H}_{11})_3$, $\text{P}(\text{C}_6\text{F}_5)_3$ and $\text{P}(p\text{-C}_6\text{H}_4\text{OMe})_3$ were tested but only tri(*p*-methoxyphenyl)phosphine showed activity under conditions similar to those employed for PPh_3 and its reactions were slower; the other phosphorus ligands produced inactive insoluble black residues during attempted reactions. Attempted catalyses using phosphite ligands $\text{P}(\text{OPh})_3$ or $\text{P}(\text{OEt})_3$ under similar conditions were also unsuccessful but in these cases it is likely that significant hydrolysis of the ligands occurred in the aqueous-alcoholic medium. It appears that Pd– PPh_3 systems are preferred catalysts but do produce some by-products, including triphenylphosphine oxide.

2-Indanone **5** was identified as a minor by-product (<5% by GC, at termination of catalysis). However, when dissolved in *t*-amyl alcohol in the presence of water and NEtPr_2^i at 70 °C (i.e., under catalytic conditions [1]), 2-indanone was shown by GC analysis to decompose completely within 2 h. Therefore, it is likely that more significant amounts of 2-indanone are formed during the course of a catalyzed reaction. The decomposition products of **5** were not identified but could be a major source of the tarry residues observed in catalytic systems.

2-Indanone has been reported as one product of decomposition in solution of the isolable bis-trimethylphosphine acyl complex **4a**, which is formed by CO insertion into the corresponding *o*-xylyl-palladium derivative, *trans*-Pd(*o*- $\text{CH}_2\text{C}_6\text{H}_4\text{CH}_2\text{Cl}$)Cl(PMe_3)₂ **3a** [12]. A mechanism involving a Pd(IV) metallacyclic intermediate **7a** has been proposed for this reaction [12], as illustrated in Scheme 2, but without definitive supporting evidence; it may be noted



Scheme 1. (L = PPh_3 or related ligand; B = base).

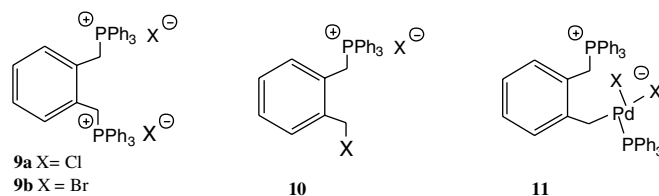


Scheme 2.

that an alternative 6-coordinate, non-ionic structure for intermediate **7a** (and also for **6a**) might equally be considered. Although trimethylphosphine complexes of palladium were found to be catalytically inactive for the synthesis of 3-isochromanone from *o*-xylylene- α,α' -dichloride under conditions used in the present study, the formation of 2-indanone in catalytic systems containing triphenylphosphine complexes may occur by a similar mechanism (i.e., **3b** \rightarrow **4b** \rightarrow **7b** \rightarrow **5**; Scheme 2). The formation of Pd(IV) species with PPh₃ ligands will be less electronically favorable than with PMe₃ but kinetic evidence for such intermediates with the former ligand has been reported [13].

Another by-product of the catalytic systems, identified primarily by NMR spectroscopy, is the bis-phosphonium compound **9a**. The maximum yield of this salt is limited by the amount of added PPh₃ but its formation removes substrate and so reduces overall conversion to lactone. Also, formation of this salt will reduce the concentration of PPh₃, which is necessary to prolong the activity of the palladium catalyst. It is of interest that only the dicationic salt is observed, whereas quaternization of compounds **2** at low PPh₃:xylylene dihalide ratios normally affords monocationic salt **10** and more forcing conditions are required to form **9** [14]. The presence of Pd complexes appears to facilitate the double quaternization and it is likely that xylyl–palladium complexes are involved in this side-reaction. A possible mechanism is the transformation of **3b**, via an intermediate Pd(IV) metallacycle **6b** (or corresponding neutral 6-coordinate species; see Scheme 2) followed by reductive elimination of one benzyl–Pd bond by combination with PPh₃, to form a Pd(II) complex such as **11**, containing a phosphoniobenzyl ligand; a second reductive elimination, with PPh₃, of Pd–C from **11** may then yield **9a**. The production of phosphonium salts by a similar mechanism has been described for triphenylphosphine–palladium complexes with aryl [15], vinyl [16,17] and alkyne [18] ligands, and ionic Pd-complexes with η^2 -phospho-

nioalkene ligands have been isolated in reactions of vinyl halides [17]. Related reactions are aryl/phenyl [19,20] and methyl/phenyl [21] interchange of complexes PdRX-(PPh₃)₂, although only in the former reaction was the participation of a phosphonium salt [PR(PPh₃)₃]X established [19,22].

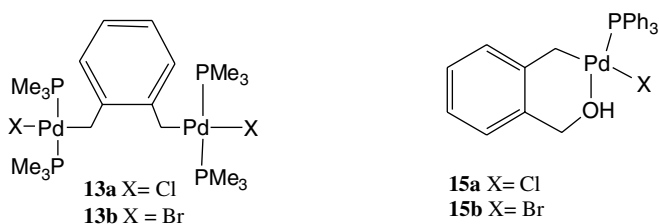


Since it is known that aryl phosphonium salts can add oxidatively to Pd(0) complexes by P–C cleavage [15] and that this reaction is also proposed as a step in aryl group exchange reactions [19,22], we considered the possibility that the xylylene group of salts **9** might be reintroduced into the catalytic cycle by Pd-activation of the benzyl–P bond. However, an equimolar mixture of **9b** and Pd(PPh₃)₄ in refluxing acetonitrile showed no evidence of reaction after 6 h so it may be concluded that the cation of salts **9** is inactive in catalytic processes operating under mild reaction conditions and that they do contribute to decreased yields of lactone **1**.

2.2. Stoichiometric reactions of *o*-xylylene- α,α' -dihalides with palladium complexes

The first step in palladium-catalyzed carbonylations of *o*-xylylene dihalides **2** to form lactone **1** is believed to be oxidative addition to palladium(0) generating a xylyl–Pd complex **3**, followed by insertion of CO, as shown in Scheme 1. Campora et al. [12] have established that such a reaction does occur between *o*-xylylene dichloride and the bis-trimethylphosphine–Pd(0) complex, Pd(η -CH₂=

CHCO₂Me)(PMe₃)₂ **12**, to form the mononuclear product **3a** at 20 °C, even when using a 1:2 ratio of reagents **2a**:**12**; only over a significantly longer time, or at 50 °C, does a second oxidative addition occur to form the binuclear species **13a**. However, even at a reagent ratio of 1:1, only binuclear **13b** is obtained from analogous reactions of *o*-xylylene dibromide at 20 °C [12]. Compounds **13** are stable in organic solvents under nitrogen but compound **3a** decomposes slowly in solution at ambient temperatures to afford PdCl₂(PMe₃)₂ and organic compounds derived from *o*-xylylene **8**, see Scheme 2. Compounds **3a** and **13** undergo insertion reactions with CO (3 atm) but, whereas diacyl products from compounds **13** are stable, the monoacyl product **4a** derived from **3a** decomposes slowly in organic solvents at 20 °C, as mentioned in Section 2.1, producing PdCl₂(PMe₃)₂, 2-indanone **5** and products from *o*-xylylene **8** [12]. Mechanisms proposed [12] for these decomposition reactions are shown in Scheme 2.



We have confirmed the observations of Campora et al. [12] and subjected a single crystal of mononuclear **3a**, obtained from dichloromethane/hexane, to analysis by X-ray diffraction. The molecular structure is depicted in Fig. 1 and important geometrical parameters are listed in Table 1. The complex is *trans*-square-planar with a structure similar to that reported for *trans*-PdBr(*p*-CH₂C₆H₄Br)(PMe₃)₂ **14** [23]. The Pd–C distance, 2.084(3) Å, is close to 2.078(13) Å of **14**; the Pd–P distances are slightly longer than those of the latter complex {2.307(5) Å and 2.297(6) Å [23]}, although closer to those reported for *trans*-PdBr(Et)(PMe₃)₂ {2.311(2) and 2.314(2) Å [24]}. In complex **3a**, the angle P(2)–Pd–Cl is 85.72(3)° with other L–Pd–L' angles in the range 90.5–92.5° and the rms deviation of atoms Pd–C(1)–P(2)–P(3)–Cl(1) from the coordination plane is 0.0722 Å; the plane of the *o*-xylylene ligand is approximately perpendicular to the coordination plane {interplanar angle Pd–C(1)–P(2)–P(3)–Cl(1)/C(1)–(8) = 86.82°} and this compares with a related angle of 85.2° in complex **14** [23]. The chloromethyl group of **3a** is remote from the metal centre with the Cl-atom readily available to form binuclear product **13a**. There is no interaction between the Pd and Cl atoms (separation 4.265 Å) and no evidence for incipient intramolecular oxidative addition but there is no steric restriction to formation of the postulated metallacyclic intermediate **6a** in solution.

Since trimethylphosphine complexes are catalytically inactive for synthesis of **1**, we investigated stoichiometric reactions of triphenylphosphine–palladium complexes with

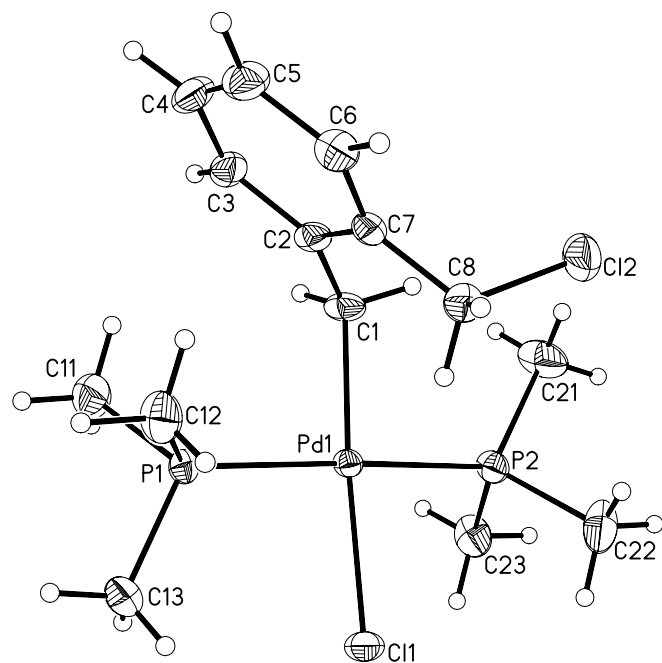


Fig. 1. Molecular structure of compound **3a** (ellipsoids drawn at the 50% probability level).

Table 1
Selected bond lengths (Å) and angles (°) of compound **3a**

Pd(1)–C(1)	2.084(3)	C(1)–Pd(1)–P(1)	91.37(8)
Pd(1)–P(1)	2.3183(7)	C(1)–Pd(1)–P(2)	90.59(8)
Pd(1)–P(2)	2.3306(7)	P(1)–Pd(1)–Cl(1)	92.46(3)
Pd(1)–Cl(1)	2.4155(7)	P(2)–Pd(1)–Cl(1)	85.72(3)
C(1)–C(2)	1.494(4)	C(2)–C(1)–Pd(1)	120.48(19)
Cl(2)–C(8)	1.815(3)	C(7)–C(8)–Cl(2)	111.9(2)

o-xylylene dihalides in attempts to gain mechanistic information about the catalytic systems. On mixing Pd(PPh₃)₄, as a source of Pd(0), with an equimolar amount of **2a** or **2b** at ambient temperature in an inert organic solvent such as toluene, solutions rapidly turned bright orange but then faded in colour over 1–2 h, precipitating poorly-soluble, yellow PdX₂(PPh₃)₂ (X = Cl or Br, respectively); analysis showed the latter was produced in high yield (ca. 90%), probably by a double oxidative mechanism via intermediates of types **3** and **6** of Scheme 2. Small amounts of bis-phosphonium salt **9** were also formed under these conditions but, as in the catalytic reactions, no mono-phosphonium species **10** was observed.

¹H NMR spectroscopic monitoring of these reactions showed formation of a new small broad resonance around δ2.81 or δ2.75, from reaction of **2a** or **2b**, respectively, as well as the small, sharp doublet at δ5.28 (*J*_{P–H} = 15.5 Hz) or δ5.25 (*J*_{P–H} = 14.6 Hz) assignable to the CH₂ groups of the bis-phosphonium salt, **9a** or **9b**. The higher field signal is consistent with a Pd–CH₂ group (cf. [9]) of a triphenylphosphine–xylyl–palladium complex **3b**, or the related bromo-derivative, formed by oxidative addition; a dipalladium species analogous to **13** is possible but less likely at such high substrate: Pd ratios. The intensity of this

resonance remained very low (<5%) throughout formation of $\text{PdX}_2(\text{PPh}_3)_2$, and it disappeared as the limiting reagent was consumed (e.g., within 45 min for **2b** in CDCl_3) indicating instability at ambient temperature and probably a steady-state existence during the reaction. Attempted isolation and purification of this unstable species for further characterization by using lower temperature reactions, and by addition of non-solvents was unsuccessful. Also, attempts to produce the product by reactions of **2a** with other triphenylphosphine–Pd(0) complexes, $\text{PdL}(\text{PPh}_3)_2$ (L = dimethylmaleate, maleic anhydride or *p*-benzoquinone), failed. The greater instability of **3b** (and its bromine analogue), in comparison with **3a**, must be associated with the greater steric requirements and, possibly, the poorer donor properties of the PPh_3 ligands. Note that in oxidative additions of *o*-hydroxymethylbenzyl halides to $\text{Pd}(\text{PPh}_3)_4$ three phosphine ligands are displaced and monophosphine complexes **15** containing a chelated hydroxy group are isolable [9]; an intermediate of similar geometry, if formed in reactions of xylylene dihalides **2**, with a Pd–halogen interaction, would provide a facile pathway for decomposition via a Pd(IV) metallacycle of type **6b**.

2.3. Structure of *o*-xylylene- α,α' -bis(triphenylphosphonium-bromide) **9b**

It was of interest to determine the molecular structure of the dicationic bis-phosphonium by-product **9**. A crystal of the dibromide salt **9b**, containing one water molecule and one methanol of solvation per molecule of **9b**, was obtained from solution in methanol and its structure was determined by X-ray diffraction. Interactions between the disordered methanol molecules and the salt are insignificant, whereas

the water molecules interact via H-bonding with bromide anions. The structure of **9b**, including a solvated H_2O , is shown in Fig. 2 and selected bond lengths and angles given in Table 2.

The structure of neutral 1,2-bis[(diphenylphosphino)methyl]benzene diselenide, *o*- $\text{C}_6\text{H}_4(\text{CH}_2\text{PPh}_2\text{Se})_2$ (dpmbSe₂), has been reported [25] and has some features analogous to **9b**, but the two P–CH₂ bond lengths of the former are slightly longer {1.832(3) Å/1.8303(3) Å, cf. 1.793(4) Å/1.806(4) Å}. The two positively charged PPh_3 groups in **9b** are mutually *trans*, with P(1)–C(1) and P(4)–C(8) bonds lying almost in the plane of the *o*-phenylene ring {torsional angles: P(1)–C(1)–C(2)–C(3) = 6.4(6)°; C(6)–C(7)–C(8)–P(2) = 4.5(6)°}; this orientation places the H-atoms of the methylene groups C(1)H₂ and C(8)H₂ in an eclipsed conformation and readily available for H-bonding with the anions. This contrasts with the structure of dpmbSe₂ in which one P–CH₂ bond points out of the *o*-phenylene plane, placing the two CH₂ groups in an approximate gauche conformation [25]. The two Br^- anions of **9b** interact with one H-atom of each methylene group {Br(1) ⋯ H(1A) 2.69 Å; Br(1) ⋯ H(8B) 2.76 Å; Br(2) ⋯ H(1B) 2.75 Å; Br(2) ⋯ H(8A) 2.95 Å}; Br(2) also closely approaches an *ortho*-hydrogen of a phenyl ring {Br(2) ⋯ H(12) 2.81 Å}. Each water molecule exhibits two H-bonding interactions with

Table 2
Selected bond lengths (Å) and angles (°) of compound **9b**

P(1)–C(1)	1.793(4)	P(2)–C(8)	1.806(4)
C(1)–C(2)	1.524(6)	C(7)–C(8)	1.525(6)
C(2)–C(7)	1.416(6)		
C(2)–C(3)	1.389(6)	C(6)–C(7)	1.391(6)
C(2)–C(1)–P(1)	119.9(3)	C(7)–C(8)–P(2)	118.3(3)
C(2)–C(7)–C(8)	117.0(4)	C(7)–C(2)–C(1)	118.1(4)

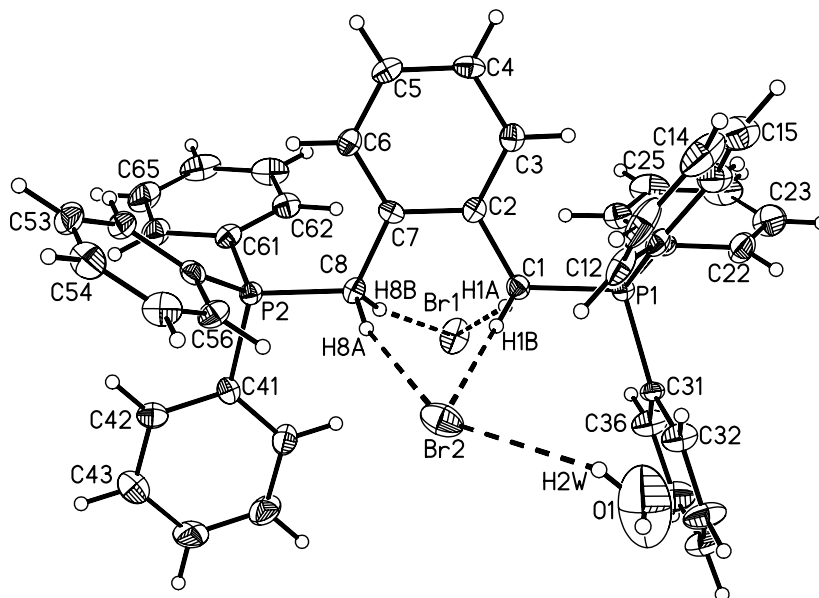


Fig. 2. Molecular structure of compound **9b** (ellipsoids drawn at the 50% probability level).

Br⁻ anions of adjacent salt molecules {H(2W) ··· Br(2) 2.95(7) Å; H(1W) ··· Br(1)#2 2.54(2) Å}.

In the solid state, the dication is slightly asymmetric but, as expected, NMR spectra are consistent with a symmetrical system in solution (e.g., singlet ³¹P NMR resonance of equivalent P-atoms at δ23.7). The ¹H NMR spectra of salts **9** do include distinctive chemical shifts for resonances of the AA'BB' grouping of *o*-phenylene hydrogens, {δ6.96 (br s) or δ6.98 (complex m) for **9a** or **9b**, respectively} which are well separated, to high field, from resonances of the phenyl groups. However, there are no unusual interactions in the solid state involving these *o*-phenylene hydrogens that might be related to this shift and it probably arises from inductive effects of the P⁺ centres and/or other interactions in solution between halide ions and this aromatic ring.

3. Conclusions

The carbonylation of *o*-xylylene- α,α' -dihalides to form 3-isochromanone **1** catalyzed by triphenylphosphine complexes of palladium involves an unstable xylyl–palladium species, probably related to the previously isolated [12] and now structurally characterized, trimethylphosphine derivative **3a**, which is more stable but catalytically inactive. Palladium complexes with a range of other phosphorus(III) ligands are also inactive or less effective catalysts than complexes with PPh₃ and this must be related to their inability to cycle readily between Pd(0) and Pd(II) states, as required in the mechanism of Scheme 1. Small amounts of 2-indanone **5** were detected at the completion of a catalytic reaction and probably arise from cyclization of a monoacyl intermediate **4**; the instability of **5** under the catalytic conditions suggests that decomposition of more significant amounts of **5**, formed during the course of reactions, is a likely source of other by-products and the cause of reduced yields of the desired lactone. Both triphenylphosphine oxide and *o*-xylylenebis(triphenylphosphonium) salts **9** are also by-products of the PPh₃-containing catalytic systems and their formation removes phosphine ligand necessary to prolong catalyst life and, in the latter case, also removes substrate reducing the yield of 3-isochromanone.

4. Experimental

4.1. General

Reactions and operations involving palladium compounds were conducted under an atmosphere of dry, oxygen-free nitrogen or argon gas, using Schlenk techniques. Solvents were dried and freshly distilled before use as previously described [9]. Tetrakis(triphenylphosphine)-palladium [26], trimethylphosphine–palladium compounds **3a**, **4a** and **13a/b** [12] and *o*-xylylenebis(triphenylphosphoniumbromide) **15b** [14] were prepared by literature methods; other reagents were obtained commercially

(Aldrich Chemicals) and used as supplied. ¹H and ¹³C{¹H} NMR spectra were recorded on Bruker AC 200 or DPX 400 spectrometers (at ca. 25 °C) using SiMe₄ as internal reference and ³¹P{¹H} NMR spectra on the DPX 400 instrument using 85% H₃PO₄ as external reference. IR spectra were recorded using a PE1600 series FTIR spectrophotometer. GC analyses were performed with a PE8310 gas chromatograph and GCMS with an HP6890 gas chromatograph [containing a HP5MS (30 m × 0.25 mm) capillary column] coupled to an HP5973 Quadrupole Mass Filter (EI, high-energy dynode/electron multiplier detector).

4.2. Syntheses, reactions and characterization

4.2.1. General procedure for homogeneous Pd-catalysed carbonylation of *o*-xylylene- α,α' -dihalide to 3-isochromanone (cf. [1c])

A solution of Pd-catalyst was prepared by stirring Na₂PdCl₄ (0.0282 mmol) in water (1 cm³) with PPh₃ (0.151 g, 0.576 mmol) and *t*-amyl alcohol (5 cm³) for 30 min under a nitrogen atmosphere. The yellow solution of preformed catalyst was then added to *o*-xylylene- α,α' -dichloride **2a** (2.5 g, 14.3 mmol), ethyldiisopropylamine (5.55 g, 43 mmol) and water (5 cm³) in a glass reactor fitted with a sintered gas inlet and condenser, and CO was bubbled slowly through this mixture. {If required, naphthalene (0.5 g, 3.9 mmol) was also added as an inert internal GC standard}. The reactor was then heated to 70 °C for periods of 0.75–2 h. GC analysis of the reaction mixture indicated complete consumption of **2a** within 1 h and the formation of 3-isochromanone (>80%), accompanied by small amounts of 2-indanone (<5%). As described previously [1], 3-isochromanone was isolated by extraction into aqueous base and re-extraction into an organic solvent after acidification, followed by distillation. (Catalyst and tertiary alcohol and amine can be recovered in this process.) The product **1** was identified by comparison with an authentic sample (IR, ¹H NMR, GC).

The above procedure was adapted for investigating systems with other phosphorus(III) ligands by replacing PPh₃ in the catalyst mixture with PMe₃, PET₃, P(C₆H₁₁)₃, P(C₆F₅)₃, P(C₆H₄-*p*-OMe)₃, P(OPh)₃ or P(OEt)₃. However, except for systems with P(C₆H₄-*p*-OMe)₃, negligible amounts of **1** were produced.

4.2.2. Reaction of *o*-xylylene- α,α' -dichloride **2a** with tetrakis-(triphenylphosphine)palladium

o-Xylylene- α,α' -dichloride **2a** (66.5 mg, 0.38 mmol) dissolved in toluene (10 cm³) was added to a stirred suspension of tetrakis(triphenylphosphine)palladium (437 mg, 0.38 mmol) in toluene (40 cm³) to produce a bright orange homogeneous solution. After stirring at ambient temperature for 2 h, the colour of solution changed to yellow and a yellow precipitate formed which was separated from solution by filtration, washed with light petroleum ether and dried in vacuo to afford a solid (237 mg) identified as

$\text{PdCl}_2(\text{PPh}_3)_2$: NMR (CDCl_3): δ_{H} /ppm 7.26–7.5 (m, 18H, PPh_3), 7.63–7.71 (m, 12H, PPh_3). Solvent was evaporated from the filtrate in vacuo to leave a yellow residue; ^1H NMR (CDCl_3) of the residue showed resonances assignable to *o*-xylylene- α,α' -bis(triphenylphosphoniumchloride) **9a** (see below) and a small amount of unreacted starting material **2a**, but no other new aliphatic ^1H resonances.

4.2.3. Reaction of *o*-xylylene- α,α' -dibromide **2b** with tetrakis(triphenylphosphine)palladium

o-Xylylene- α,α' -dibromide **2b** (264 mg, 1.0 mmol) dissolved in dry, degassed toluene (20 cm^3) was added to a stirred suspension of tetrakis(triphenylphosphine)palladium (1.15 g, 1.0 mmol) in toluene (70 cm^3), immediately producing a bright orange homogeneous solution. After stirring for 15 min the solution was cooled to 0 °C and petroleum ether (b.p. 60–80 °C) (70 cm^3) was added. A yellow-orange solid precipitated from the mixture, which was isolated by filtration and dried in vacuo. On dissolving this solid in CDCl_3 , (or in deuterated benzene, toluene or acetonitrile) the solution changed within 1 min from pale orange to bright yellow. ^1H NMR analysis of the yellow solution (CDCl_3) indicated the presence of $\text{PdBr}_2(\text{PPh}_3)_2$: δ_{H} /ppm 7.25–7.52 (m, 18H), 7.63–7.79 (m, 12H); also, a broad, weak signal δ 2.75 but no other aliphatic resonances. (A weak signal at δ 2.75 was also observed by monitoring the ^1H NMR spectra in early stages of reactions of **2b** with $\text{Pd}(\text{PPh}_3)_4$ carried out in CDCl_3 ; spectra also contained

small resonances assignable to *o*-xylylene- α,α' -bis(triphenylphosphinebromide) **9b**, see below).

4.2.4. Synthesis of *o*-xylylene- α,α' -bis(triphenylphosphinechloride) **9a** (cf. [14])

o-Xylylene- α,α' -dichloride **2a** (0.5 g, 2.86 mmol) and triphenylphosphine (3.0 g, 11.44 mmol) were dissolved in acetonitrile (70 cm^3) and heated under reflux for 6 h. Cooling to rt and refrigeration at 5 °C, afforded the *title product* as a white, crystalline solid which was collected by filtration, washed with diethyl ether (3 \times 20 cm^3) and dried in vacuo (832 mg, 42%); m.p. >300 °C; NMR (CDCl_3): δ_{H} /ppm 5.28 (d, J_{HP} 15.5 Hz, 4H, CH_2P), 6.96 (br s, 4H, C_6H_4), 7.6–7.9 (m, 30H, C_6H_5); NMR (CD_2Cl_2): δ_{H} /ppm 5.53 (d, J_{HP} 15.3 Hz, 4H, CH_2P), 6.93 (m, 4H, C_6H_4), 7.59–7.87 (m, 30H, C_6H_5).

4.2.5. NMR data for *o*-xylylene- α,α' -bis(triphenylphosphinebromide) **9b**

NMR (CDCl_3), assignments made by DEPT, HMQC, COSY, NOESY: δ_{H} /ppm 5.25 (d, J_{HP} 14.6 Hz, 4H, CH_2), 6.98 (m, 4H, C_6H_4), 7.62–7.88 (m, 30H, PPh_3); δ_{C} /ppm 28.4 (d, J_{CP} 50 Hz, CH_2), 117.9 (d, J_{CP} 86 Hz, PPh_3 , *ipso*-CP), 128.5 (C_6H_4 , CH-3 or 4), 129.4 (d, J_{CP} 8 Hz, C_6H_4 , *quat*-CCH₂), 130.4 (d, J_{CP} 13 Hz, PPh_3 , *o*- or *m*-CH), 132.4 (d, J_{CP} 4 Hz, C_6H_4 , CH-4 or 3), 134.4 (d, J_{CP} 10 Hz, PPh_3 , *m*- or *o*-CH), 135.1 (PPh_3 , *p*-CH); δ_{P} /ppm 23.7 (s, $\text{CH}_2\text{P}^+\text{Ph}_3$).

Table 3
Crystal and structure refinement data

Compound	3a	9b · H ₂ O · CH ₃ OH
Empirical formula	C ₁₄ H ₂₆ Cl ₂ P ₂ Pd	C ₄₅ H ₄₄ Br ₂ O ₂ P ₂
Formula weight	433.59	838.57
Crystal system	Monoclinic	Monoclinic
Space group	<i>P</i> 2(1)/ <i>n</i>	<i>P</i> 2(1)/ <i>n</i>
Unit cell dimensions (Å)/(°)	<i>a</i> = 11.2888(14)/ α = 90 <i>b</i> = 14.1676(9)/ β = 105.244(8) <i>c</i> = 12.0999(10)/ γ = 90	<i>a</i> = 11.847(2)/ α = 90 <i>b</i> = 15.943(3)/ β = 94.820(10) <i>c</i> = 21.028(3)/ γ = 90
Volume (Å ³)	1867.1(3)	3957.7(11)
<i>Z</i>	4	2
Density (calculated) (Mg/m ³)	1.542	1.307
Absorption coefficient (mm ⁻¹)	1.438	1.586
<i>F</i> (0 0 0)	880	1572
Crystal size (mm ³)	0.18 \times 0.84 \times 0.36	0.68 \times 0.46 \times 0.21
θ Range data collection (°)	2.20–25.00	1.91–25.00
Index ranges	–1 $\leq h \leq$ 13, –16 $\leq k \leq$ 1, –14 $\leq l \leq$ 14	–1 $\leq h \leq$ 14, –18 $\leq k \leq$ 1, –25 $\leq l \leq$ 25
Reflections collected	4156	8617
Independent reflections	3288 [R_{int}] = 0.0311]	6926 [R_{int}] = 0.0649]
Completeness to maximum θ (%)	99.8	99.3
Maximum/minimum transmission	0.7187 and 0.4823	0.9619 and 0.5713
Data/restraints/parameters	3288/0/172	6926/1/473
Goodness-of-fit on F^2	1.053	1.051
Final R indices [$I > 2\sigma(I)$]	R_1 = 0.0302, wR_2 = 0.0801	R_1 = 0.0549, wR_2 = 0.1237
R indices (all data)	R_1 = 0.0324, wR_2 = 0.0817	R_1 = 0.0886, wR_2 = 0.1393
Largest difference in peak and hole (e Å ⁻³)	0.475 and –0.657	1.083 and –0.752

4.3. X-ray data collection and crystal structure determinations

Single crystals of complex **3a** were grown by slow diffusion of hexane into a solution in dichloromethane at $-15\text{ }^{\circ}\text{C}$ and of **9b**, solvated with methanol and water, by slow evaporation of a solution in methanol. Crystals were mounted on a glass fibre and data collected with a Siemens P4 diffractometer. All datasets were collected with Mo $K\alpha$ radiation (0.71073 \AA) at $160(2)\text{ K}$ with cooling by an Oxford Cryosystems Cryostream. Absorption was corrected for using psi-scans and structure refinement was by full matrix least squares against F^2 [27]. For both structures, H atoms were constrained to idealized geometries; except in **9b** where the water H atoms, which were found in the difference Fourier map and the O–H distances restrained to $0.90(2)\text{ \AA}$. The hydroxyl H atom was not included in the model of the methanol solvent, where the carbon atoms were disordered over two sites. One carbon was assigned $2/3$ occupancy and the hydrogen atoms bound to this atom were given full occupancy because hydrogen atoms were not modeled at the minor position for the CH_3 ($1/3$ occupancy). A summary of the data from the crystal structure determinations is given in Table 3.

5. Supplementary material

Crystallographic information files (CIF) have been deposited with Cambridge Crystallographic Data Centre: CCDC reference numbers 2283696 and 2283697 for **3a** and **9b**, respectively. Copies of this information can be obtained free of charge by application to The Director, CCDC, 12, Union Road, Cambridge CB2 1EZ, UK (fax: +44 1223 336033; e-mail: deposit@ccdc.cam.ac.uk or <http://www.ccdc.cam.ac.uk>).

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