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METALLATED PHOSPHITES AND RELATED COMPLEXES AND THEIR CATALYTIC APPLICATION

A thesis submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy

University of Dublin

By

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December 2001

Declaration

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P. Noelle Scully

P. Noelle Scully

To My Parents,
John and Annie
And my Partner,
Martin.

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Summary

The orthometallation of triarylphosphite ligands at a palladium centre is described. The formation of the orthometallated palladium dimeric complex $[\{Pd(\mu\text{-}Cl)\{P(OC_6H_2\text{-}2,6\text{-}{}^tBu_2)(OC_6H_3\text{-}2,4\text{-}{}^tBu_2)_2\}\}_2]$ **22** is reported and fully characterised by X-ray, ^{31}P NMR and microanalysis. Complex **22** was found to be an active catalyst in the Heck, Suzuki and Stille coupling reactions. It is an extremely active catalyst in the Heck arylation of alkenes, with turnover numbers of up to 5,750,000 (mol product.mol Pd^{-1}) and turnover frequencies of up to nearly 300,000 (mol product.mol Pd^{-1}.h^{-1}), amongst the highest reported to date. Complex **22** is also an extremely active catalyst in biaryl coupling reactions, giving unprecedented turnover numbers of up to 1,000,000 (mol product.mol Pd^{-1}) and turnover frequencies of nearly 900,000 (mol product.mol Pd^{-1}.h^{-1}) in the Suzuki reaction and turnover numbers of up to 830,000 (mol product.mol Pd^{-1}) in the Stille reaction.

The synthesis of the triarylphosphite palladium anion complex $[Pd\{P(OC_6H_3\text{-}2,4\text{-}Bu^t_2)_3\}_2Cl_3][Et_3NH]$ **(30)** is also reported, and found to be active in the Suzuki coupling.

The palladium complexes, $[Pd\{OC(O)CF_3\}\{C_6H_3\text{-}2,6\text{-}(OPPh_2)_2\}]$ **37a** and $[Pd\{OC(O)CF_3\}\{C_6H_2\text{-}4\text{-}CH_3\text{-}2,6\text{-}(OPPh_2)_2\}]$ **37b** of inexpensive bis(phosphinite) 'PCP'-pincer ligands are also reported and show good activity in the Suzuki coupling of deactivated and sterically hindered aryl bromides with turnover numbers of up to 190,000 (mol product.mol Pd^{-1}) achieved. The complexes are fully characterised by ^{31}P, ^1H NMR and microanalysis. The X-ray structure of complex **37a** is also described.

The synthesis of sulphur and methylene bridged triarylphosphite ligands are also reported. The reaction of some of these new ligands with palladium dichloride is described. The of X-ray structures of the nonmetallated palladium anionic methylene bridged triarylphosphite complex $[Pd(Cl)_3\{(CH_2[(2\text{-}t\text{-}Bu)(4\text{-}Me)C_6H_2O]_2)P(O\ C_6H_32,4\text{-}Me)\}\{Et_3NH\}]$ **(56)** and of the metallated palladium dimer $[Pd(\mu\text{-}Cl)_2\{(CH_2[(2\text{-}t\text{-}Bu)(4\text{-}Me)C_6H_2O]_2)\}P(OC_6H_3\text{-}2,4\text{-}Me)]$ **(57)** are also described.

Abbreviations

Ac	acetyl
Br	broad
Bu	butyl
^{t}Bu	tertbutyl
CaH_2	calcium hydride
cm^{-1}	wavenumbers
Cp	cyclopentadiene
d	doublet
DCM	dichloromethane
DMA	dimethyl acetamide
DMF	dimethyl formaide
dppe	diphenylphosphinoethane
Et	ethyl
Et_3N	triethylamine
Et_2O	diethylether
GC	gas chromatography
IR	infra red
^{i}Pr	isopropyl
KF	potassium fluoride
m	meta
Me	methyl
Mes	2,4,6-tri-methylphenyl
$MgSO_4$	magnesium sulphate
NMR	nuclear magnetic resonance
o	ortho
p	para
Ph	phenyl
t	triplet
TFA	trifluoroacetic acid
TOFs	turnover frequencies
Tol	tolyl

TONs	turnover numbers
THF	tetrahydrofuran
s	singlet
X	halide

Chapter 1

Introduction

Orthometallated Complexes as Active Site Masks

Introduction

1.1 Organophosphorus Chemistry – a brief history.

The organic chemistry of phosphorus is based on the existence of numerous stable functional groups that contain the carbon-phosphorus bond or that are organic derivatives of inorganic phosphorus acids.[1] Organophosphorus chemistry had its beginnings in the nineteenth century with in 1847 P. E. Thénard producing trimethylphosphine from methyl chloride and impure calcium phosphide.[2] After the discovery of aliphatic amines, the relationship between amines and phosphines stimulated A. W. von Hoffmann, and then Cahours,[3] to develop this area of chemistry, with K. A. A. Michaelis synthesising triphenylphosphine in 1885.[4] It was F. G. Mann[5] who began the explosion of interest in transition metal phosphine chemistry.[6] Since then, the chemistry of organophosphorus complexes has expanded into a vast range of sub-areas, for example metal hydrides,[7] nitrogen fixation,[8] stability of unusual oxidation states,[9] metal alkyls and aryls,[10] and vast areas of homogeneous and heterogeous catalysis.[11] This project involves the study of phosphorus(III) ligands such as phosphines, phosphites and phosphinites with emphasis on the role they play in catalysis.

1.2 Bonding in phosphorus

Phosphorus is a non-metal and its bonding is covalent. However phosphorus can form stable pentacoordinate compounds such as PCl_5, which for non-metals is extremely rare. One explanation for this may be that phosphorus is a second row element and it has a larger number of bonds per atom, therefore is capable of forming pentacoordinate compounds. Also second row elements have empty 3d orbitals, which can be used to expand their coordination sphere. To examine the bonding of phosphorus it is important to look at the nature of the covalent bond and also the spatial arrangement of such bonds[12]. The valence-shell electron pair repulsion theory (VSEPR) is a simple way of looking at the bonding and geometry of the phosphorus molecules without actually going into the bonding theory in detail. PX_3 molecules have four electron pairs in their valance shell, which adopt a tetrahedral configuration. However one pair is non-bonding so the angle between it and the bonding pair is wider than the angle between the bonding pair themselves. In comparison to the nitrogen analogues the non-bonding pair in phosphorus has a greater effect. Therefore the shape of a PX_3 molecule should be pyramidal with a sharper angle at the phosphorus apex than the corresponding NX_3. Tetracoordinate phosphorus cations such as PH_4^+ have the four bonding electron pairs tetrahedrally arranged about the phosphorus atom. When phosphorus is surrounded by five electron pairs in its valence shell there is no possible way in which the five electron pairs can be arranged so that they are equivalent. It is found that pentacoordinate compounds adopt a trigonal bipyramidal configuration. The three equatorial atoms of such a structure are nearer to the central phosphorus atom than the axial atoms. The axial bonding-pairs experience repulsion from three electron pairs while the equatorial bonding-pairs experience only two electron pairs. Which results in lengthen of the axial bonds and shorten of the equatorial bonds. By increasing the electronegativity of the ligand attached to the phosphorus atom the more it will assist in this process.[12]

1.2.1 Tricoordinate phosphorus compounds

Phosphorus has the same kind of ground state electron configuration, [Ne] $3s^2$ $3p^3$, as nitrogen [He] $2s^2$ $2p^3$ this would suggest that a certain degree of similarity in their chemistry.[12] However, this is not the case. The main cause of difference between the behaviour of phosphorus and nitrogen compounds comes from the strength of the bonds they form with other elements. Bond angles are always smaller in phosphine derivatives than in their nitrogen counterparts. This is explained in terms of the relative contributions of the s and p orbitals to the bonding. If phosphorus uses its 3p orbitals for bonding then its non-bonding pair must reside in the 3s orbital. Hence the lone pair of PH_3 is less available than NH_3. However, as the s character of the bonds increase so does the p character of the lone pair therefore making it less diffuse and more available.[12] The nature of the ligand attached to the phosphorus plays an important role in the performance of the lone pair. For instance the introduction of methyl groups has a major effect on the basicity, more so than in nitrogen chemistry. The lone pair on phosphorus also has an effect on the dipole moment. As the dipole moment for PF_3 is less than that of PMe_3 despite the fact that the polarity of the phosphorus-fluorine bond is greater than that of the phosphorus-methyl bond.[12]

1.2.2 Phosphorus(III) ligands in transition metal complexes.

The phosphorus derivatives used as ligands tend to be the simple and symmetrical PX_3 type, among which PH_3, PF_3, PCl_3, $P(OMe)_3$, $P(OEt)_3$, PR_3 (R= alkyl, aryl) have been most used.[12] To explain the particularly good bonding capabilities of PX_3 ligands it was proposed by Chatt[13] that the donor σ bond formed between the ligand and the metal was reinforced by a donor nd(M)→3d(P) π back bonding from the metal to the phosphorus (Figure 1.1).

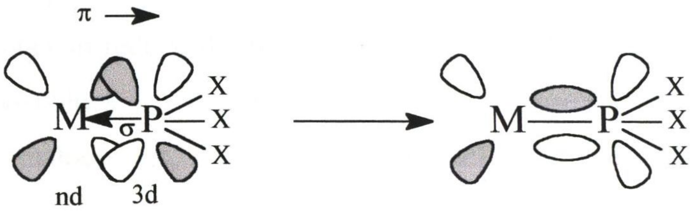


Figure 1.1 Bonding between a π-acceptor ligand and a metal

Phosphorus(III) ligands are seen as members of a group of ligands referred to as π-acceptor ligands, which include carbonyl, nitrosyl etc. These ligands of first row elements have no 3d orbitals but are still able to relieve the metal of electrons by accepting them into unoccupied antibonding orbitals. Hence they can stabilise metal complexes in low oxidation states such as M(0) or even M(-1).

Phosphorus(III) ligands with less electronegative atoms or groups attached such as PR_3 and PH_3 are not considered as π-acceptor ligands. In order to explain this the ligand field contraction must be considered as only strongly electronegative atoms can sufficiently contract the 3d(P) orbitals to make them suitable for π-bonding.

1.3 Phosphines

1.3.1 Structure and Properties

The chemistry of phosphines is centred on the presence of a lone pair that allows for the formation of new bonds to the phosphorus atom. It is the donation of the lone pair to electrophilic centres that is responsible for most of the reactivity of phosphines. Phosphines like their nitrogen counterparts amines have a pyramidal geometry but unlike amines, phosphines are unable to undergo inversion. Phosphines have a fixed pyramidal structure. It is known that the Carbon-Phosphorus-Carbon (C-P-C) bond angles in tertiary phosphines expand as group size increases so the increase in steric size of the P- substituents can reduce the reactivity by hindering the approach of reagents to the lone pair.[14] Phosphines can be difficult to handle, because they are sensitive to the atmosphere, highly malodorous, toxic and the lower alkyl derivatives are spontaneously inflammable.[1]

1.3.2 σ Bonding and the Bascitiy of Phosphines

The Metal-Phosphorus (M-P) bond is a donor covalent bond with the phosphorus providing both electrons, *i.e.* behaving as a Lewis base. In general, electron-releasing substituents will increase the electron availability on phosphorus; so therefore comparing triphenylphosphine to the dimethylaminophenyl substitution results in a greatly enhanced basicity. As the steric bulk of the substituent group on phosphorus increases the R-P-R angle increases, this will increase the p character of the lone pair (figure 1.2).[6] The stability of the metal-phosphorus σ *bond* decreases[15] in the series: $PBu^t_3 > PR_3 \sim PPh_3 > P(OR)_3 > PH_3 > PF_3 > P(OPh)_3$.

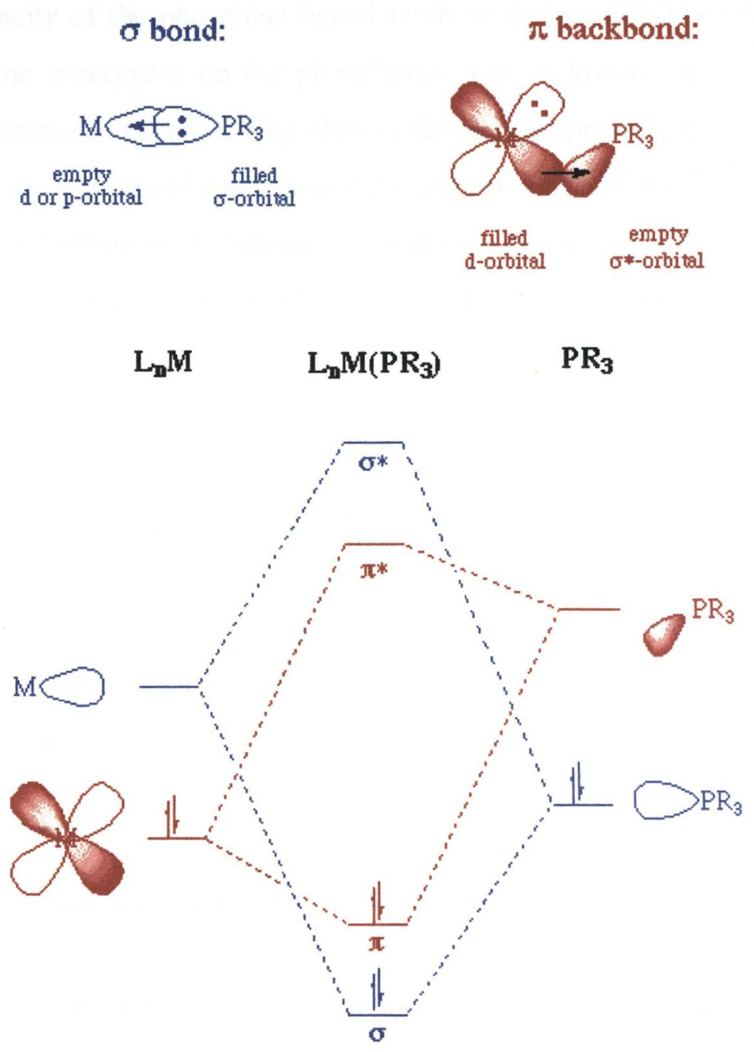


Figure. 1.2 Molecular Orbital Diagram

1.3.3 π Bonding in Phosphine Complexes

The phosphorus-transition metal back bonding is a transfer of charge from the metal to the ligand. This is described as π bonding because of the symmetry of the orbitals involved. In the case of an octahedral complex, the *d* orbitals involved in σ bonding with the six ligands are the e_g orbitals, leaving the t_{2g} orbitals non-bonding and directed between the six M-P bonds (figure 1.2).[6] The primary phosphorus-metal bond is the σ bond formed between a d^2sp^3 metal hybrid orbital and an sp^3 hybrid phosphorus orbital. On coordination the bonding between the PR_3 changes from pyramidal sp^3 to tetrahedral sp^3. As electron-withdrawing groups are placed on the phosphorus atom, the σ-donating capacity of the phosphine ligand tends to decrease. While this is happening the energy of the π-acceptor on the phosphorus atom is lowered in energy therefore, providing an increase in back bonding ability. Hence, phosphines can exhibit a range of σ-donor and π-acceptor capabilities, and the electronic properties of a metal centre can be tuned by the substitution of electronically different but isosteric phosphines. Listed in Figure 1.3 is an empirical ordering of the π-acidity σ-donor capabilities of phosphine and related ligands.

$PMe_3 < PPh_3 < P(OMe)_3 < P(OPh)_3 < P(NR_2)_3 < PCl_3 < CO \sim PF_3$

$\longrightarrow$ Greater π-acidity $\longrightarrow$

$\longleftarrow$ Greater σ-donation $\longleftarrow$

Figure 1.3 σ-donor/π-acceptor abilities of phosphorus compounds as compared to carbon monoxide

1.3.4 Synthesis of Phosphines

Phosphines can be synthesised by various different routes, most of which are listed below with a brief discussion. The most important precursors are those containing P-halogen bond, or alkali metal derivatives.[6]

1.3.4.1 From Phosphorus halides

Phosphorus dihalides are used as starting materials for tertiary phosphines of the type RR'_2P or R_3P. The reaction of the dihalide with a slight excess of an organometallic reagent results in the replacement of the two halogens to give the desired phosphine.

1.3.4.2 From Metal phosphides

The anions from PH_3 are excellent nucleophiles and are highly reactive to alkylation reagents. This method is the most commonly used synthetic route for phosphines especially for the synthesis of phosphines as ligands. The anions are prepared by reaction of the phosphine with the metal (usually sodium, potassium or calcium) in liquid ammonia or with butyllithium. The product is then reacted stoichiometrically with the alkylating reagent to give the desired phosphine.

1.3.4.3 From Organic Phosphines

Primary and secondary phosphines can add to carbon-carbon multiple bonds by a radical or an ionic mechanism.[6] Phosphine adds to the double bond of alkenes in the presence of one equivalent of an acid (sulfonic acids, liquid HF, BF_3) to form the salt of a primary phosphine, which prevents further alkylation occurring.

1.3.4.4 From 4-Coordinate Compounds

Tertiary phosphine oxides can be reduced under mild conditions to synthesise phosphines also phosphonic esters can be reduced by $LiAlH_4$ as a way to produce phosphines.

1.4 Phosphites

As ligands for transition metal complexes, phosphites were relative latecomers and it was their ability to orthometallate, which sparked an interest of such complexes in homogeneous catalysis.[12]

1.4.1 Structure and Properties

Phosphite ligands are closely related to phosphines and have the general formula of $P(OR)_3$. Like phosphines the chemistry of phosphites is centred on the presence of a lone pair on the phosphorus atom, which allows them to coordinate to a metal centre. These complexes are often similar to those of phosphines but phosphites are less sterically hindered and therefore have a smaller cone angle than phosphines. This is attributed to the presence of the oxygen atom as it acts as a spacer. Phosphites are easier to handle because they are less sensitive to the atmosphere and less malodorous than their phosphine counterparts.

1.4.2 σ Bonding of Phosphites

The electronegative nature of the alkoxy group which is present on the phosphorus atom of phosphites results in the decrease of σ bonding capabilities of phosphites compared to phosphines. Hence, the stability of the metal-phosphorus σ bond is slightly less than that of phosphines.

1.4.3 π Bonding in Phosphite Complexes

The π acidity of $P(OR)_3$ type ligands is higher relative to PR_3 ligands, therefore phosphites are better able to stabilising a metal complex by π-backbonding. The lowering of the π orbitals allows for backbonding to occur.

1.4.4 Synthesis of Phosphites

Phosphites can be synthesised from various different routes, which are listed below. The easiest and simplest approach is the reaction of phosphorus trichloride with three equivalents of an alcohol in the presence of a base such as triethylamine or pyridine (this is described in greater detail in chapter 5).

1.4.4.1 From Phosphorus trichloride

Phosphorus trichloride is used as starting material for triaryl phosphites. The reaction of phosphorus trichloride with three equivalents of an alcohol in the presence of a base yields triaryl phosphites in reasonably good yields.[16] This method is easy and fast. For the less bulky triaryl phosphites reaction times can be as short as one hour long. However, for the more bulky triaryl phosphites the reaction times can be somewhat longer (up to 18 h).

$$PCl_3 + 3\,ArOH \xrightarrow[Ether]{Base} P(OAr)_3 + 3\,HCl$$

1.4.4.2 From Phosphorodichloridites[17]

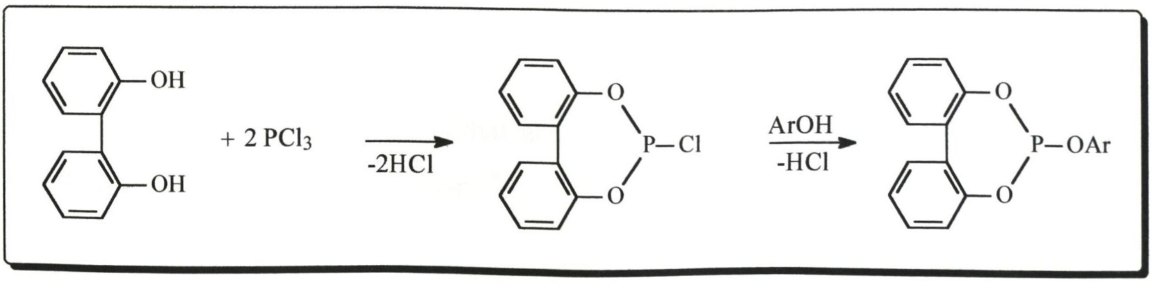
The reaction of phosphorus trichloride with equimolar proportions of an alcohol results in the formation of the phosphorodichloridite. Simply by replacing the chlorides with an appropriate alcohol, the desired phosphite can be synthesised. This method can be used to form phosphites with a different range of R groups attached.

$$1 \quad PCl_3 + ArOH \xrightarrow{Base} ArOPCl_2 + HCl$$

$$2 \quad ArOPCl_2 + 2\,ROH \xrightarrow{Base} ArOP(OR)_2 + 2\,HCl$$

1.4.4.3 From Phosphorochlorides[18]

This method is used for the synthesis of phosphites which contain a bridging link between one or more of its aryl groups. The reaction of a bridged diol with one equivalent of phosphorus trichloride forms the appropriate phosphorochlorides. This is then reacted with a phenol to give a bridged phosphite.



1.5 Transition metal complexes in organic synthesis

Transition metals play a very important role in the industrial synthesis of organic chemicals.[19] They are applied for the synthesis of fine chemicals either catalytically or stoichiometrically as shown below in figure 1.4. Generally catalytic routes are the preferred in industrial applications as opposed to stoichiometric ones.

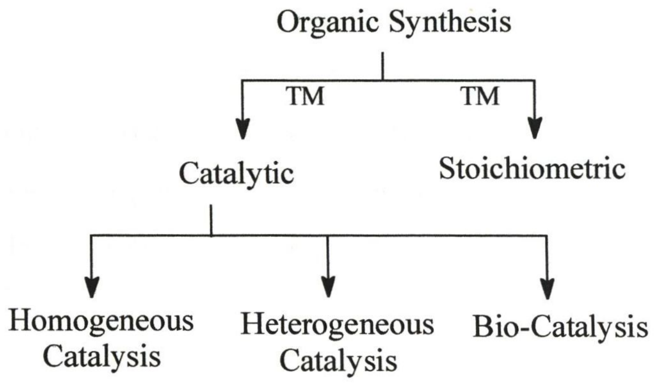


Figure 1.4 Transition metals in organic synthesis

From an industrial point of view, heterogeneous systems have a greater advantage over homogeneous systems. This is due to the fact that for heterogeneous systems it is easier to separate the product from excess reactant and catalyst at the end of the catalytic cycle. However, a number of homogeneous systems have been developed as they show high selectivity and operate under milder conditions than the heterogeneous analogues.[20]

The following is a list of reactions that are used in organic synthesis based on transition metal catalysed or mediated reaction.[19]

Oxidation: Oxidation reactions are extensively used in the synthesis of fine chemicals.[21] In the past many stoichiometric oxidations were carried out with traditional oxidants like permanganate and dichromate, which produced large amounts of waste causing problems in disposal. In order to overcome this problem a wide range of processes were looked at with the most successful one, being the Wacker process (scheme 1.1). The oxidation of ethylene by palladium(II)-copper(II) chloride solutions is essentially quantitative and only low concentrations of palladium are required. The mechanism for the oxidation of palladium metal by copper(II) chloro complexes is complex and not very clear but electron transfer via halide bridges is probably involved.[20] The extremely rapid air oxidation of copper(I) chloro complexes is better known and probably proceeds via an initial oxygen complex, followed by formation of radicals such as O_2^-, OH^- or HO_2. Oxidation of alkenes gives ketones e.g. acetone from propene.[19]

$$
\begin{array}{rcl}
C_2H_4 + PdCl_2 + H_2O & \longrightarrow & CH_3CHO + Pd + 2HCl \\
Pd + 2CuCl_2 & \longrightarrow & PdCl_2 + 2CuCl \\
2CuCl + 2HCl + \tfrac{1}{2}O_2 & \longrightarrow & 2CuCl_2 + H_2O \\
\hline
C_2H_4 + \tfrac{1}{2}O_2 & \longrightarrow & CH_3CHO
\end{array}
$$

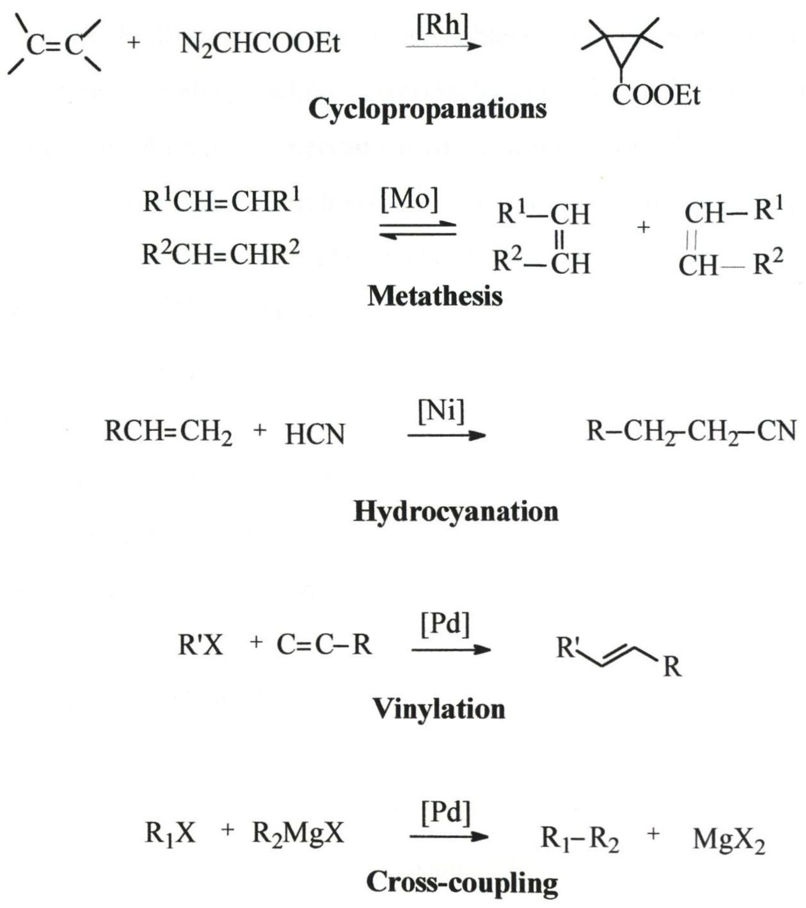
Scheme 1.1 The Wacker process

Hydrogenation: Hydrogenation reactions can be heterogeneously operated in fixed bed or slurry *i.e.* palladium on carbon, platinum on carbon, but also organometallic compounds are finding a broad range of applications in hydrogenation catalysis. The most common homogeneous catalyst used for hydrogenation reactions is Wilkinson's catalyst $RhCl(PPh_3)_3$. The main advantages of homogeneous catalysts compared to their heterogeneous counterparts are:[19]

- Mild operating conditions
- Chemoselective reduction of one organic function in the presence of other reducible functions, *e.g.* selective reduction of carbon-carbon double bond in the presence of $-CHO$, $-NO_2$ or $-CN$.
- Regioselective hydrogenation of just one of several similar reducible groups.
- Enantiomeric reductions made possible by using chiral ligands.

Carbon-carbon bond formation: This embraces a wide range of reactions such as: C-C linkage of alkenes, C-C linkage of dienes, telomerisation,[22] C-C linkage of alkynes.

The formation of new carbon-carbon bonds is a very important process in organic synthesis. Some examples of the use C-C bond formation reactions are given in scheme 1.2[19]



Scheme 1.2 C-C coupling reactions

Isomerisation reactions: Isomerisation reactions of double bonds are easily catalysed by transition metals.

Reactions with carbon monoxide: A great variety of possibilities exist some of which are hydroformylation, hydrocarboxylation, carbonylation of alcohols, carbonylation of halides, carbonylation of organometallics, carbonylation of nitrogen containing functional groups.[23]

Asymmetric synthesis: Chirality plays an important role in organic synthesis. Therefore, recently there has been a large interest in the formation of enantiomerically pure compounds. Asymmetric catalysis is a kinetic phenomenon where the chiral ligand discriminates the prochiral features of the bound substrate by differences in reaction rates associated with the formation of one or other of the product enantiomers.

Asymmetric hydrogenation has been achieved for carbon-carbon double bonds by using ruthenium catalysts while enantioselective hydrosilylation, hydrocyanation, hydroformylation of alkenes, isomerisation of allylamines *etc*. have also been achieved by using chiral phosphine complexes.[20] Asymmetric syntheses are used in the production of pharmaceuticals, agrochemicals, flavours and fragrances.

Polymerisation: The discovery by K. Ziegler that hydrocarbon solutions of $TiCl_4$ in the presence of Et_3Al give heterogeneous suspensions that polymerise ethylene at 1 atm pressure has led to an extremely diverse chemistry in which aluminium alkyls are used to generate transition metal-alkyl species. The Ziegler-Natta system is heterogeneous, and the active metal species is a fibrous form of $TiCl_3$ formed *in situ* from $TiCl_4$ and $AlEt_3$. However, since then many improvements have been made.[20]

1.6 Active Site "Masking"

The presence of an active site in a metal complex is vital for catalysis. An active site can equate to a vacant co-ordination site. It can activate substrates both stoichiometrically and catalytically, hence making the generation of an active site a vital step in catalysis. An active site is also a possible way to introduce a change in the oxidation state of a complex. The classical method for the formation of an active site is the dissociation of a bulky ligand from a complex. However, in order for this to occur, the residual ligands must be relatively sterically encumbered; therefore the size of the incoming ligand is limited. A closely related method is the use of hemi-labile chelate ligands, that is one in which one donor readily dissociates from the metal site, hence leaving a vacant co-ordination site (Figure 1.5 a).

An active site can also be "unmasked" by reductive elimination of two fragments from the co-ordination sphere (figure 1.5 b). The resultant complex is not only co-ordinatively unsaturated, but also reduced and therefore able to undergo facile oxidative addition reactions.

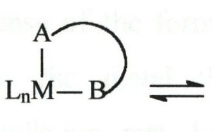


Figure 1.5 a

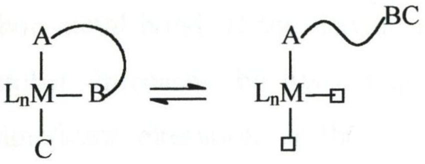


Figure 1.5 b

□ = vacant coordination site

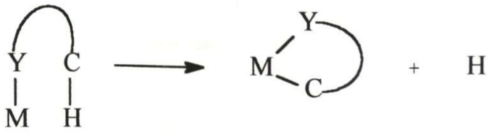
The current study focuses on the use of triarylphosphite ligands that can act as an active site "mask" by employing one of the above processes and on the application of the resultant masked complexes in catalytic and stoichiometric reactions.

1.6.1 Triarylphosphites as Active Site "Masks"

Two general methods for masking an active site with triarylphosphite ligands can be envisaged these are **(1.6.1.1)** Orthometallation mechanisms and **(1.6.1.2)** Hemi-Labile Phosphites, as outlined below.

1.6.1.1 Orthometallation Mechanisms.[24,25]

The basic mechanisms of the formation of cyclometallated complexes involve direct metallation of C-H bond where, Y is any centre, which is either co-ordinating with or covalently bound to the metal centre (eq. 1.1).



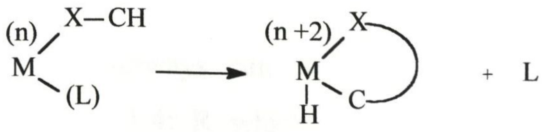
Eq 1.1 Cyclometallation

Designation of the leaving group as [H] – specifies neither the nature of the leaving atom (proton, hydride, or radical) nor whether it remains bound to the metal or dissociates with an appropriate leaving group. The above equation shows that the co-ordination number of the central atom may increase on cyclometallation by one unit at the expense of the formation of a novel carbon-metal bond. If the leaving group [H] binds to the metal the co-ordination number increases by two units. Hence, cyclometallation may be accompanied by significant alteration in the co-ordination sphere. The oxidation state of the central atom could be unchanged in the initial and final complexes. In this case, the complex must part with one ligand if the leaving hydrogen dissociates, or with two, if the hydrogen binds directly to the metal. However at the same time a co-ordinatively saturated complex must often discard some ligands to create the vacant site in its co-ordination sphere, which is necessary for cleavage of the C-H bonds. The ability of complexes to become co-ordinately unsaturated is therefore an important prerequisite of cyclometallation.

There are three general mechanisms of C-H cleavage:

i) Oxidative Addition
ii) Electrophilic Substitution
iii) Multicentred Pathway

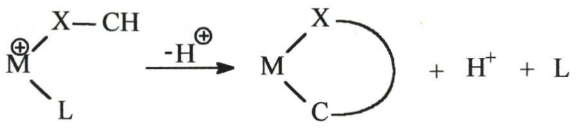
i) For a facile oxidative addition reaction (eq. 1.2), the reactive complex must have an empty σ-type molecular orbital (MO) and a high-energy MO containing the lone pair which will be transferred into the σ^*-orbital of the H-C bond during the oxidative addition reaction.[25]



Eq 1.2 Oxidative Addition of a C-H bond

The C-H bond formally receives two electrons from the central atom, hence the oxidation state (n) of the metal increases by two units. If the hydride remains in the co-ordination sphere after the cleavage of the C-H bond, oxidative addition is likely to be the mechanism of cyclometallation (the metal can be considered here as a nucleophilic centre).

ii) In straightforward electrophilic mechanisms metal hydrides do not form, the central atom does not change its oxidation state (n), and hydrogen dissociates as a free or bound proton (eq. 1.3)



Eq 1.3 Electrophilic Substitution

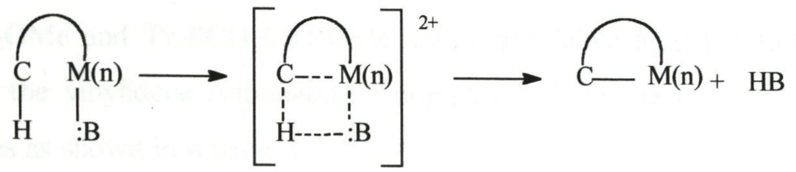
Both of the above routes have been proposed mainly from reaction studies, in which phosphorus donor ligands have been involved, pathway (ii) is thought to be generally operative.[26]

Two alternative mechanisms for orthometallation of triarylphosphite donor ligands are as follows:

(a) metal insertion into the C-H bond of a co-ordinated ligand (oxidative addition of the ligand C-H moiety of the metal followed by reductive elimination);

(b) electrophilic displacement of a proton by the metal at the carbon centre.

iii) Formally multi-centred pathways can be written as a nucleophilically assisted electrophilic displacement (eq. 1.4: R which may be alkyl, benzyl or phenyl groups replaces the base :B). For the multi-centred pathway to occur the reactive species needs only to have an empty acceptor MO to stabilise the entering σ-bond electron pair in the transition state.[27]



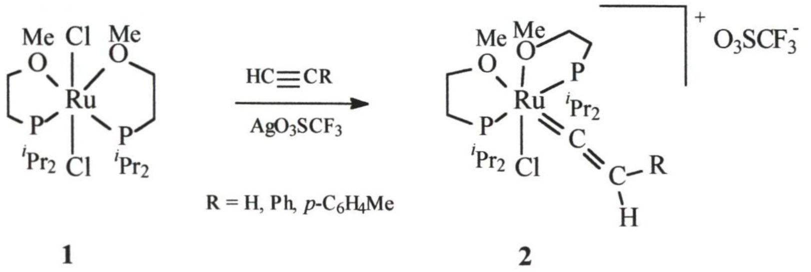
Eq 1.4 Multi-centred pathway

1.6.1.2 Hemi-Labile Ligands as Active site Masks.

It is known that late transition metal complexes can be stabilised by alkyl and arylphosphine ligands. The soft donor properties of the ligand allow it to form stable bonds to the transition metal. It is possible to synthesise multidentate phosphine ligands that contain a soft donor site as well as a hard donor site. The hard donor may coordinate only weakly to the metal centre and thus can be easily displaced by another ligand. This property has been termed hemilabile.[28]

This second approach to active site masking describes the use of triarylphosphite and related ligands that has one or more hemi-labile donor groups attached (*c.f.* chapter 5). The process in which a hemilabile ligand can mask an active site is depicted in equaton 1.3. This shows a weakly bound hard donor group B that dissociates from the metal centre with ease to leave the metal with a vacant coordination site, which can bind an incoming ligand. It is possible for hemilabile ligands to stabilise reactive intermediates by reversible coordination of the hard donor. For instance Werner *et al.* have studied the coordination chemistry of the hemilabile ligands iPr$_2$PCH2CH2Y (Y = OMe or NMe) and found that the resultant complexes can be used to stabilise independently unstable groups such as alkylidynes,[29a] vinylidenes,[29] allenylidenes,[29a,b,d,30] and alkylidynes[29e]. It is possible to synthesise bi-functional ether-phosphines which have an oxygen atom incorporated in an open chain or cyclic ether moiety. The oxygen atom can then form a weak metal-oxygen bond while the phosphorus atom is strongly coordinated to the metal centre. It has been reported that the ether oxygen donor may be regarded as behaving like an intramolecular solvent molecule preserving the increased reactivity of "solvated" organometallic species while the hemilabile nature of the ligand makes the complexes much more stable than simple solvent adducts.[31]

In 1996 Werner and co-workers showed that the etherphosphine ligands $^{i}Pr_2PCH_2CH_2OMe$ and $^{i}Pr_2PCH_2C(O)OMe$ act as hemilabile ligands which support the formation of the vinylidene ruthenium(II) complex **2** from the reaction of complex **1** with 1-alkynes as shown in scheme 1.3.[32]



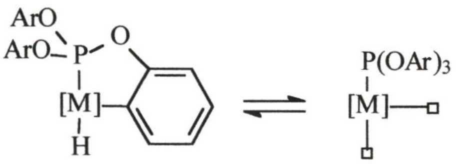
Scheme 1.3 Reaction of a hemilabile chelate complex to produce a cationic vinylidene ruthenium complex.

The strength of the metal oxygen bond depends upon four factors[30], which are listed below;

i) The nucleophilicity of the oxygen atom
ii) The size of the chelate ring
iii) The number and position of the oxygen atom in the chelate ring
iv) The acidity of the metal centre

Similarly, complexes with hemilabile phosphorus–oxygen and phosphorus–nitrogen ligands have been found to facilitate several stoichiometric and catalytic transformations of organic molecules such as acetylene to vinylidene tautomerisations.[33] These type of complexes have been used as effective catalysts for olefin oligomerisation, polymerisation, carbonylation of methanol and methyl acetate and hydrogenation catalysis.[34] The cationic palladium η^3-allyl complexes with bidentate ω-(diphenylphosphino)carboxylic acid ester ligands are known to be active catalysts for the cooligomerisation of carbon monoxide with ethylene[35] and for the codimerisation of ethylene and styrene.[30,34-36]

Triarylphosphites can introduce an active site "mask" in two possible ways. Firstly, triarylphosphites readily undergo orthometallation reactions at transition metal centres (as described in section 1.4.1.1). The reverse, de-orthometallation, provides a metal complex with two vacant coordination sites and a low oxidation state (figure 1.6). Triarylphosphites facilitate this process by their ability to stabilise the low oxidation state of the transition metal by their enhanced π acidity. Secondly, with the presence of a heteroatom such as nitrogen or sulphur and depending on the metal centre the ligand can function as a hemi-labile chelate (as described in section 1.4.1.2).



□ = vacant coordination site

Figure 1.6 De-orthometallation reaction

1.7 Cyclometallation reactions of Triarylphosphites

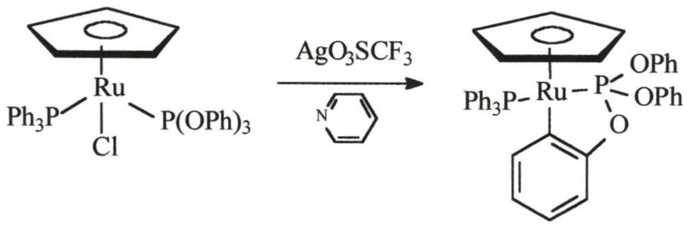
Triarylphosphites can readily undergo cyclometallation reactions to give organometallic compounds with a carbon-phosphorus-metal bond with the carbon atom linked to the metal (figure 1.5). Two important factors, which are believed to promote internal metallation in such complexes, are:

i) The ability to form five-membered chelate rings on metallation

ii) The presence of bulky substituents on the tertiary phosphite.

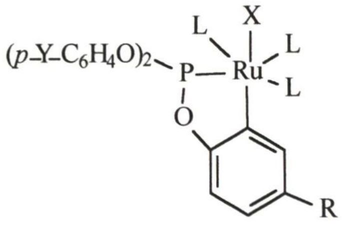
Intramolecular orthometallation of coordinated triarylphosphites affords five-membered chelate rings. This ring size is favoured due to steric strain interactions. It is therefore not surprising that these ligands undergo metallation relatively easily. On the other hand, triarylphosphines almost always form four-membered chelate rings, which is considerably less favourable in terms of ring strain. This is best demonstrated by the preferential orthometallation of the triphenylphosphite ligand over the triphenylphosphine in the ruthenium complex shown in scheme 1.4.

Under the same conditions (pressure and temperature), no cyclometallation occurs with $[RuCpCl(PPh_3)_2$ or $[RuCpCl(PPh_3)\{P(OMe)_3\}]$.[37]



Scheme 1.4 Cyclometallated triarylphosphite complex

Examples of orthometallation reactions involving triarylphosphite ligands coordinated to ruthenium (figure 1.7),[27] rhodium[38]and manganese[39] (figure 1.8), iridium (figure 1.9),[40] palladium and platinum[41] have been observed.[42]



X = Cl, Y = H
X = Br, Y = H
X = Cl, Y = Me
X = Br, Y = Me

Figure 1.7 Orthometallated ruthenium

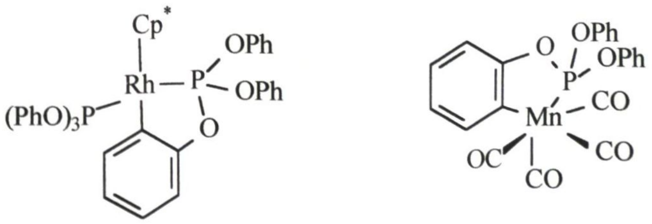


Figure 1.8 Orthometallated rhodium and manganese complexes

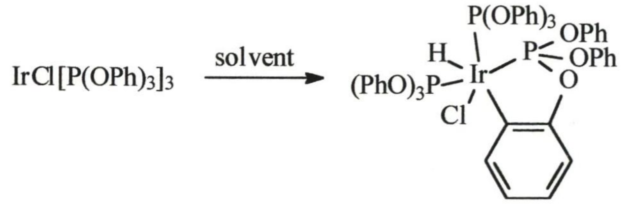
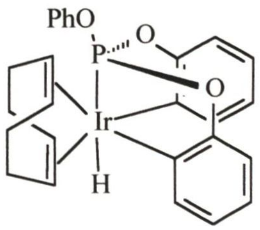


Figure 1.9 Orthometallated Iridium complex

1.7.1 Orthometallated Iridium Complexes

It was found that the reaction of triphenylphosphite with $[Ir(cod)(py)_2][PF_6]$ in methanol did not lead to the di-orthometallated species **3**[43] but gave the bis-phosphite complex **4** (see diagram below) which was previously reported by Singleton in 1970.[44] This can be attributed to the relatively low cone angle of triphenylphosphite which is a result of its low steric bulk therefore less favouring the di-orthometallated species.



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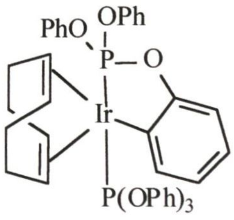

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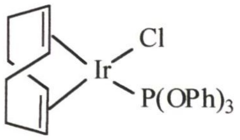
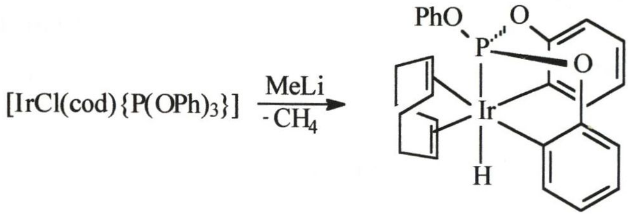


5

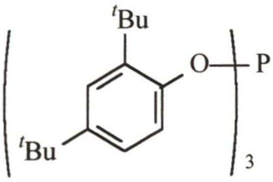
In order to overcome this problem it was first thought that the use of complex **5** as a starting material where only one coordinated phosphite is present, once refluxed in methanol to facilitate orthometallation by hydride transfer should be suffice to yield the desired complex **3**.[43] However, this proved to give a mixture of the di-orthometallated complex and the bis-phosphite complex.[43] Therefore it was necessary to use an alternative route. It was found that upon methylation of the bis-phosphite complex followed by reductive elimination of methane gave complex **3** (scheme 1.5) as air stable crystals in 47 % yield.[43]



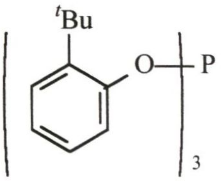
3

Scheme 1.5 Synthesis of di-orthometallated iridium complex

It is worth noting that the preparation of analogous di-orthometallated iridium complexes of tris(2,4-di-*tert*-butylphenyl)phosphite **6** and tris(2-*tert*-butylphenyl)phosphite **7** is considerably easier (scheme 1.6).[45]

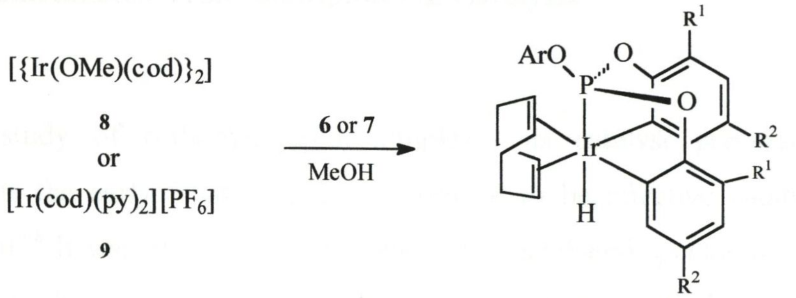


6



7

The reaction of $[\{\mathrm{Ir}(\mu\text{-OMe})(\mathrm{cod})\}_2]$ **8** with **6** in methanol leads to the formation of $[\overline{\mathrm{IrH\{P(OC}}_6\mathrm{H}_2\text{-2,4-}{}^t\mathrm{Bu}_2)_2(\mathrm{OC}_6\mathrm{H}_3\text{-2,4-}{}^t\mathrm{Bu}_2)\}(\mathrm{cod})]$, **10** in 56 % yield.[45]



10 Ar = $C_6H_3\text{-}2,4\text{-}{}^tBu_2$, $R^1 = R^2 = {}^tBu_2$

11 Ar = $C_6H_3\text{-}2, \text{-}{}^tBu$, $R^1 = {}^tBu_2$, $R^2 = H$

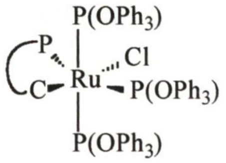
Scheme 1.6 Synthesis of di-orthometallated iridium complex with bulky ligands

Similarly, the reaction of **8** with **7** in methanol yields the complex $[IrH\{P(OC_6H_3\text{-}2\text{-}{}^tBu_2)_2(OC_6H_4\text{-}2\text{-}{}^tBu_2)\}(cod)]$, **11**, in 92 % yield (scheme 1.6).[45] **10** can also be produced in a 87 % yield, from the reaction of **6** and $[Ir(cod)(py)_2][PF_6]$ **9** in methanol. While **11** was prepared in a similar manner in 55 % yield.[45]

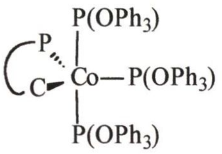
It appears therefore, that the ease of di-orthometallation of the bulky triarylphosphite ligands is a consequence of the steric bulk of the phosphite. This may be due to the fact that the complexes containing two bulky ligands are unlikely to be thermodynamically stable, as previously demonstrated by the reaction of $[Ir(cod)(py)_2][PF_6]$ with bulky triarylphosphines.[46] The mechanism of formation of the di-orthometallated complexes depends on whether the starting iridium complex is neutral or cationic, with deprotonation of a cationic hydride being a fundamental step in the latter process. Also, di-orthometallation may be favoured over mono-orthometallation as a means of minimising intramolecular interaction between the *tert*-butyl groups in the phosphite ligands.[46] However, the previously reported formation of $[\{IrH(\mu\text{-}SR)(CO)\{P(OC_6H_4\text{-}2\text{-}{}^tBu)(OC_6H_5\text{-}2\text{-}{}^tBu)_2\}\}_2]$ from $[\{Ir(\mu\text{-}SR)(CO)_2\}_2]$ ($R = (CH_2)_3NMe_2$) and 1-*tert*-butyltriphenylphosphite indicates that this is not invariably the case.[47]

1.7.2 Orthometallated Triarylphosphites in Catalysis

The study of orthometallated complexes as catalyst precursors was first investigated in the early 1980s where they proved to be effective catalysts for olefin hydrogenation.[48] It was clear that the presence of a metallated species was necessary for catalytic activity because it was shown that the nonmetallated species was inactive as a catalyst. For example the metallated triarylphosphite ruthenium complex $Ru(P(OC_6H_4)(OC_6H_5)_2(P(OC_6H_5)_3)_3Cl$ **12** and the metallated cobalt complex $Co(P(OC_6H_4)(OC_6H_5)_2(P(OC_6H_5)_3)_3$ **13** were active catalysts for ethylene and 1-hexene hydrogenation (scheme 1.7) whereas the nonmetallated complexes $RuHCl(P(OPh_3)_4$, $CoH(P(OPh_3)_3$ were inactive.[48]



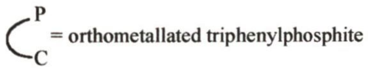
12



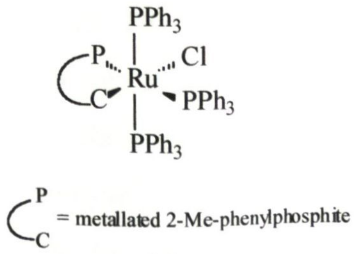
13

$$C_2H_4 + H_2 \xrightarrow[200°C]{\text{catalyst, toluene}} C_2H_3$$

Scheme 1.7 Hydrogenation of ethylene



Similarly the metallated ruthenium complex $Ru(P(OC_6H_3\text{-}2\text{-}Me)(OC_6H_5\text{-}2\text{-}Me)_2(P(C_6H_5)_3)_3Cl$ **14** was quite active under mild conditions, as a catalyst for hydrogenation of a variety of olefins that possess a number of functional groups including alkyl, phenyl, ester, siloxane, keto and cyano groups.[48]



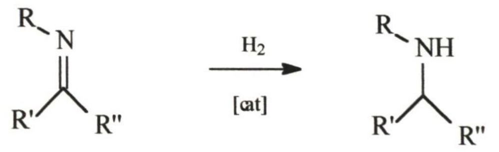
14

Complex **14** is more active than Wilkinson's catalyst for hydrogenation of both terminal and internal olefins. Even though **14** is not as active as $RuHCl(PPh_3)_3$, one of the most active homogenous hydrogenation catalysts it has significant advantages. **14** is far more air stable than $RuHCl(PPh_3)_3$ which decomposes easily and **14** can be used many times. Orthometallated ruthenium complexes such as **12** are used as a selective catalyst for the ortho-deuteration of phenols.[48,49]

1.7.3 Orthometallated Iridium complexes as imine hydrogenation catalysts

The catalytic hydrogenation of imines has attracted considerable interest in recent years, especially when the imines are prochiral.[50] Processes have been developed using titanium,[51] rhodium,[52] ruthenium,[53] and iridium[54] complexes as catalysts.

Scheme 1.8 outlines the catalytic hydrogenation of imine substrates.

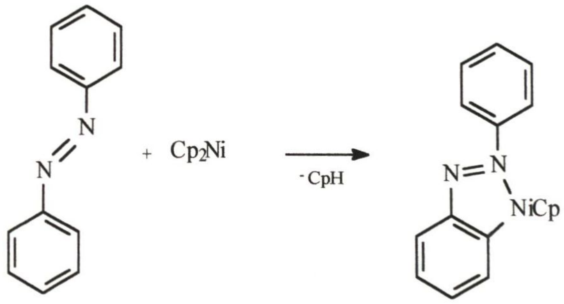


Scheme 1.8 Catalytic imine hydrogenation

The use of iridium triarylphosphite complexes as precatalysts in the homogenous catalytic hydrogenation of *N*-benzylidene aniline has been studied recently.[45] The catalytic activity of two complexes **10** and **11** (scheme1.6) were compared. Both contain di-orthometallated ligands where the main difference was found to be in the steric bulk of the ligands. The results of hydrogenation with **10** and **11** were both good, with the reactions complete within three hours. The hydrogenation rate for **11** after one hour is better than that for **10** (99 % compared to 48 %).[45] This maybe attributed to its lower steric bulk. However, after just three hours both catalysts have reached 99 % conversion. The rate of reaction catalysed by **10** is reduced to 20 % conversion after one hour when one equivalent of the free phosphite **6** is present,[45] suggesting that a monophosphite species may be more reactive than the species containing two bulky ligands.[45] Both complexes are an 18-electron Ir(III) species that are normally considered as catalytically inactive. However, the presence of a hydride ligand *cis* to a metallated ring helps de-orthometallation to occur which would give a 16-electron Ir(I) complex that is catalytically active.[45] This can be described as an example of active site masking by metallation of a triarylphosphite ligand, as the reverse process gives a complex with a vacant coordination site at the metal centre, which is an important factor in the activation of these species for catalysis.[45]

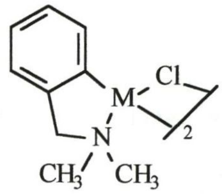
1.7.4 Brief history of cyclometallated palladium complexes

The cyclometallation reaction was discovered in 1963 by Kleinman and Dubeck.[55] They reacted azobenzene with $NiCp_2$ and obtained a five-membered metallacycle (scheme 1.9). This type of reaction is particularly interesting in the understanding of CH activation in catalytic cycles.[56]



Scheme 1.9 First example of a cyclometallated complex.

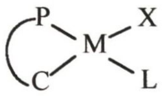
Recently, orthometallated palladium complexes have received considerable attention as they have proved efficient catalysts in carbon-carbon bond formation reaction such as the Heck and Suzuki reactions.[19] The first metallated palladium complexes were synthesised in the 1960's and consisted of a metallated amine ligand. It was shown in 1968 by Cope *et al.* that *N,N*-dimethylbenzylamine undergoes facile metallation with palladium(II) and platinum(II) chlorides to give the metallated amine complexes **15** and **16**.[57]



15 M = Pd
16 M = Pt

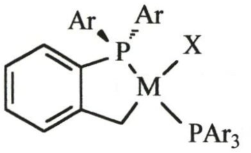
It was in the early 1970's when both Shaw and Robinson independently investigated the orthometallation of phosphine and triarylphosphite derivatives of palladium(II) and platinum(II) dihalides.[41,58,59]

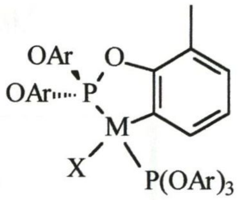
In 1972 Shaw and co-workers showed that certain complexes of the type *trans*-$[MX_2L_2]$ (X = Cl, Br or I; L = tertiary phosphine) can undergo internal metallation to give the complexes *trans*-[MX(P-C)L] **17** (P-C = internally metallated tertiary phosphine L).[58]



17 M = Pd, Pt

At the same time Robinson and co-workers were investigating the orthometallation of coordinated triaryl phosphite ligands. These were derived from triaryl phosphite derivatives of palladium and platinum dihalides, $MX_2[P(OAr)_3]_2$.[59] It was also discovered in this work that intramolecular attack for *o*-tolylphosphine occurs at the *o*-methyl group as opposed to the ortho position of the aryl ring **18**. Invariably this is not the case for tri-*o*-tolyl phosphite where the reverse situation prevails; the attack occurs at the aromatic CH group **19**.[41] The difference in behaviour between the *ortho*-tolyl phosphine and phosphite complexes may-be attributed to the steric requirements of the resultant chelate ring. This was one of the first illustrations of the importance of sterochemical factors in promoting and directing these reactions.[41]



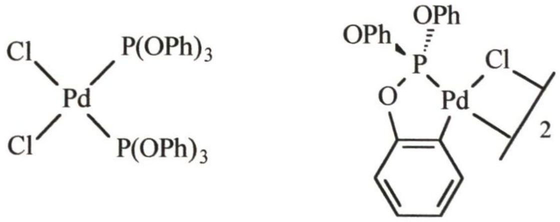


M = Pd, Pt
Ar = 2-MeC_6H_4

18

19

In 1990 Albinati *et al.* reported on the synthesis and NMR spectroscopy of cyclopalladated tertiary phosphite complexes. Scheme 1.10 illustrates an example of a monodentate and a cyclopalladated phosphite complex. Prior to this work the yields for cyclometallated phosphites of Pd(II) complexes were modest and the spectroscopic possibilities limited. [60]

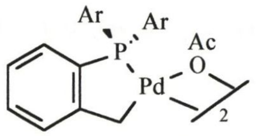


Scheme 1.10 Monodentate and cyclopalladated phosphite complex

Simply by refluxing the monodentate phosphite complex with one equivalent of palladium dichloride in a high boiling point liquid such as toluene or xylene an increase in yield from 50 % to 80 % yield was observed. This improvement can be attributed to the removal of hydrochloric acid via a slow stream of nitrogen during the refluxing period and the choice of a moderate reaction temperature.[60]

Generally, metallacycles are divided into two groups: Most examples are *ortho*-metallated complexes in which an aromatic carbon atom adjacent to a functional group is bound to the metal centre and the others are complexes in which an sp^3-carbon atom is metallated.

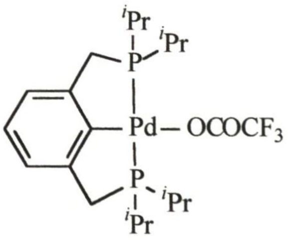
In 1995 Herrmann and co-workers reported on the synthesis of the metallated palladium complex $Pd_2(P(o\text{-}Tol)_3)_2(\mu\text{-}OAc)_2$ **20**.[61]



Ar = 2-MeC_6H_4

20

This complex was derived from tris(mesityl)phosphine and $Pd(OAc)_2$ in high yields. This palladacycle was shown to be an effective catalyst for the Heck reaction with aryl bromides especially ones with electron-withdrawing groups (COMe, CHO, CN), with high turnover numbers (TONs) of up to 10^6 being obtained. This sparked a resurgence of interest in cyclopalladated complexes as catalysts. Milstein and co-workers developed bis-chelate 'PCP'-pincer type complexes **21**.[62]

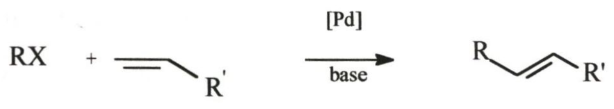


21

These complexes proved to be less effective when compared with Herrmann's palladacycle but are exceptionally thermally robust and air stable. Numerous publications have since been reported on these type complexes as Heck and Suzuki catalysts. In contrast to this work this report involves the synthesis and characterisation of palladated phosphite and phosphinite[63] complexes and the investigation into their use as potential catalysts in the Heck[64] and Suzuki[65] coupling reactions.

1.8 The Heck reaction

The synthesis of arylated and vinylated olefins is a fundamental importance in organic synthesis. The palladium-catalysed carbon-carbon coupling of haloalkenes and haloarenes with alkenes, generally known as the Heck reaction, provides an efficient gateway into such compounds.[66]
As shown in scheme 1.11 styrenes and dienes can be prepared directly from the corresponding alkenes and substituted aryl or vinyl compounds.



X = Cl, Br, I, N_2BF_4, OTf, COCl, SO_2Cl
R = aryl, vinyl

Scheme 1.11 The Heck olefination reaction.

The possibility of not only preparing simple terminal or 1,2-disubstituted olefins but also numerous complex molecular frameworks, *e.g.* tertiary and quaternary stereogenic centres, via the Heck reaction has ensured that this methodology has become one of the most important transition-metal catalysed transformations in organic synthesis. In addition to olefins and dienes, alkynes can also be used as unsaturated compounds.[67]

The synthetic utility of the Heck reaction can be explained as follows:

(i) The methodology is amenable to a variety of easily available starting materials. In general R must be an aryl or vinyl group however similar reactions of benzyl-X or allyl-X are known;

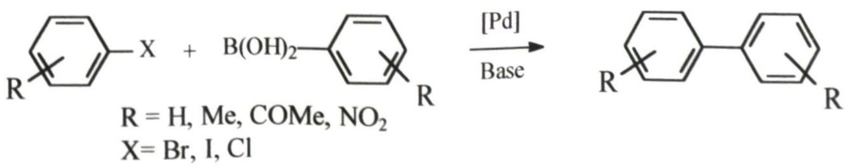
(ii) The Heck reaction is remarkably chemoslective. Hence, educts containing the most functional groups may be used and;

(iii) The palladium catalysts typically employed are air and moisture stable. In addition, palladium intermediates of the catalytic cycle of the Heck reaction can, in principle, undergo various domino reactions. Thus, polycyclisation, olefination-carbonylation or olefination-alkynylation and other domino sequences are possible.

Since its discovery in the late 1960s, the Heck reaction has become one of the most versatile and powerful tools for the selective construction of carbon-carbon bonds starting from olefins. The method has found numerous applications in the synthesis of natural products, fine chemicals and pharmacologically interesting compounds. The last decade has seen tremendous progress in catalyst efficiency for Heck reactions of simple terminal olefins. However, most Heck reactions described in natural product synthesis still need a catalyst amount of 5-20 mol%. In addition to more active catalysts, more selective palladium catalysts, which prevent side reactions, e.g. olefin isomerisation, are needed. Finally, more applications in natural product synthesis using aryl chlorides, bromides, mesylates and diazonium salts instead of the more expensive and reactive aryl iodides and triflates are needed to make the Heck reaction even more useful and economical.

1.9 Biaryl Cross Coupling Reactions

There has been considerable interest in biaryl cross coupling of aryl halides with organoboron compounds (Suzuki cross coupling reaction)[68] or organotin compounds (Stille cross-coupling reaction).[69] Due to the increasing industrial applications of Suzuki and Stille coupling reactions it is a desirable goal to design catalysts which show high activity. Considering the fact that metallated palladium complexes contain a ligand that coordinates to the metal centre through both a donor atom and a metallated carbon potentially it should serve as an active catalyst. Beller *et al.* demonstrated that the metallated complex $Pd_2(P(o\text{-}Tol)_3)_2(\mu\text{-}OAc)_2$ **20** showed good activity in the Suzuki cross coupling reactions of aryl halides with phenylboronic acids.[70]



Scheme 1.12 Suzuki Biaryl Cross Coupling Reaction

1.10 The Current Study

Little or no attention has been shown in the use of bulky triarylphosphite ligands to undergo metallation at a palladium centre resulting the formation of a metal complex which contains a 'masked' active site on the palladium centre. Considering the relative ease of synthesis and metallation of triaryl phosphite and phosphinite ligands and not to mention the low cost of the starting materials involved, palladated complexes of these systems are attractive as potential catalysts. With this in mind studies described in this thesis concentrate on the synthesis and characterisation of both triarylphosphite and phosphinite ligands and their relevant palladium complexes. At the outset of the studies described in this thesis the use of palladacycles as catalyst in Heck, Suzuki and Stille coupling reactions was still in its infancy. Furthermore, it is desirable to obtain a catalyst that can be used in low concentrations in order to increase their attractiveness to industrial applications. Likewise the use of catalysts at room temperature is another major advantage for industrial applications.

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Chapter 2

Orthopalladated Triarylphosphite Complexes As Highly Efficient Catalysts In The Heck Reaction

2.1 Introduction

2.1.2 The Heck Reaction.

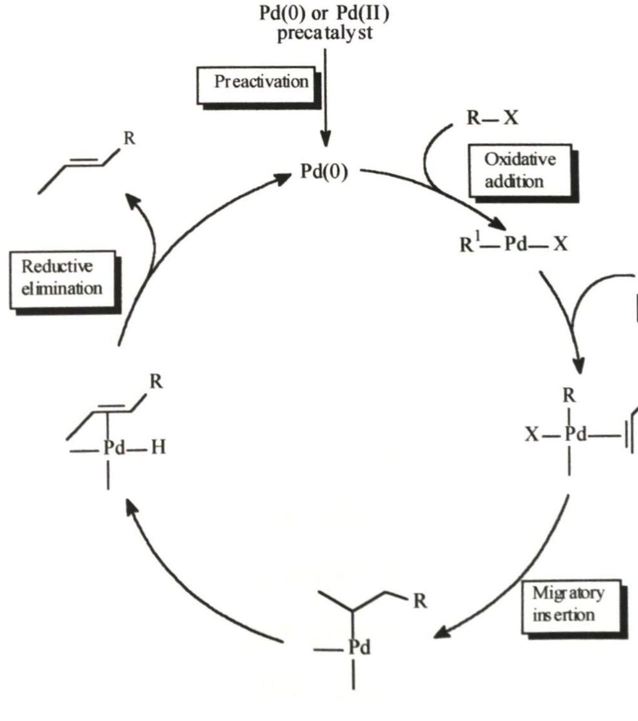
Heck type chemistry has become one of the most basic tools in organic preparations. It may be considered as a natural way to assemble molecules as a catalytic process for Carbon-Carbon (C-C) bond formation. Since the discovery of the Heck reaction in 1971, styrene derivatives, amongst others, can be prepared as vinylic C-C coupling products in one step from iodo- and bromoarenes.[1] The original reaction involved the catalytic arylation and alkenylation of olefins and since has been generally referred to as the Mizoroki-Heck reaction, as it was discovered independently by Mizoroki[2] and Heck[3] but developed by Heck into a general method of organic chemistry. The reaction presents one of the simplest ways to obtain variously substituted olefins, dienes and other unsaturated compounds. These types of compounds are used in the pharmaceutical and fine chemical industries as dyes, and UV screens. Another important aspect of the reaction is its use in polymerisation chemistry as it is possible to give access to conjugated polymers, which maybe used as new materials for optoelectronic devices.[4]

Palladium catalysis has become a widely studied field, with special attention paid to its application in the Heck reaction.[5]

The generally accepted mechanism for the Heck reaction is shown in scheme 2.1. A coordinatively unsaturated 14-electron palladium(0) complex, usually with weak donor ligands such as triarylphosphines is assumed to be the catalytically active species.[1] This complex is generally generated in *situ.* To date tetrakis(triphenylphosphine)palladium [$Pd(PPh_3)_4$] which exists in an equilibrium with tris(triphenylphosphine)palladium [$Pd(PPh_3)_3$] and free triphenylphosphine in solution is frequently used as the catalyst for the Heck reaction.[6] The endergonic loss of a second phosphine ligand[7] leads to the catalytically active bis(triphenylphosphine)palladium [$Pd(PPh_3)_2$] and free triphenylphosphine in solution. However, palladium(II) complexes, which are easily reduced in the reaction medium are more commonly used for convenience as they are inherently air stable. Some of the most common palladium(II) complexes used in the Heck reaction are [$(PPh_3)_2PdCl_2$] and palladium acetate, which are easily reduced by addition of phosphine ligand in the reaction medium.[5]

2.1.3 The Mechanism

The first step of the catalytic cycle (in scheme 2.1) is the oxidative addition of the haloalkene or haloarene to the coordinatively unsaturated palladium(0) complex to generate a σ-alkenyl or σ-aryl palladium(II) complex. As the electrophilicity of this complex increases, it more readily accepts an alkene molecule in its co-ordination sphere, probably by exchange for another ligand. The next step involves the insertions of the alkene into the palladium-arene (Pd-Ar) bond. This insertion process occurs via a four-centred transition state that requires a planar assembly of the alkene and Pd-Ar. Hence, insertion proceeds in a *syn* manner generating a σ-alkylpalladium complex. Therefore β-hydride elimination can occur, and finally reductive elimination of HX from H-PdL$_2$-X, aided by the presence of base, which regenerates the active catalysts and there-by completes the catalytic cycle.[5]



Scheme 2.1: Proposed catalytic cycle for the Heck reaction

The rate-determining step of the catalytic cycle is dependent on the starting materials employed. Therefore, the nature of the leaving group X affects the rate of oxidative addition, ArI > ArBr >> ArCl. Hence, oxidative addition is probably the rate-determining step. The electronic nature of the alkene substrate also affects the regioselectivity. Electron rich olefins react faster via a cationic pathway while electron poor olefins react faster via a neutral pathway.[8]

2.1.4 The Catalysts

Palladium complexes with or without phosphine ligands can catalyse the Heck reaction.[4] The palladium(0) phosphine complexes such as $[Pd(PPh_3)_4]$ are the classic and well established systems which give excellent results in a majority of cases for the Heck reaction, so therefore why use anything else?[4]

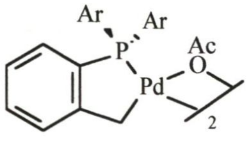
The main disadvantages of using phosphine-containing complexes as catalysts for the Heck reaction are:

- **(i)** Phosphine ligands are expensive
- **(ii)** Toxic
- **(iii)** Air and moisture sensitive
- **(iii)** Unrecoverable

therefore making large industrial scale applications unattractive. Similarly, by using phosphines that are fully coordinated to the palladium complex may result in the complex been too stable, and as a consequence higher loads of the complex are needed to obtain reasonable conversions. Another major problem is the separation of the products from the expensive palladium complex. Intense efforts have been undertaken in recent times to develop more active and productive catalysts in order to use the synthetic power of Heck and related reactions in large-scale industrial synthesis.[9]

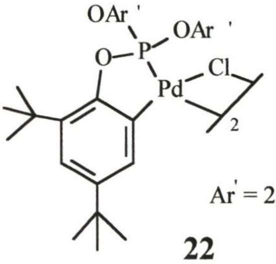
2.2 Aim of Research

The use of phosphines in the Heck reaction has attracted much attention over the recent years. In the early 1980s Spencer [10] was among the first to pioneer the improvement of productivity of the Heck reaction. He showed that the arylation of olefins with activated aryl bromides can be achieved at low catalyst concentrations, yielding high TONs when the reaction is carried out in polar aprotic solvents (i.e. DMA, DMF) in the presence of sodium acetate and tris(mesityl)-phosphine as ligand. It was during the course of this work that the palladacycle **20** was first discovered however no advantages were noted until Herrmann *et al.* rediscovered it in 1995.[11]



Ar = 2-MeC_6H_4

20



Ar' = 2,4-$^tBu_2C_6H_3$

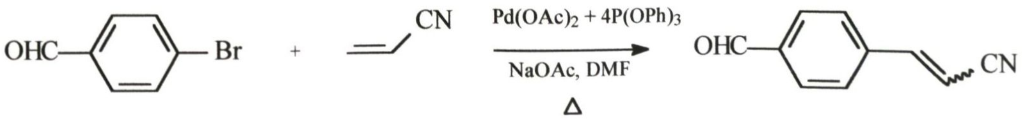
22

Further to this, studies were carried out to obtain the most active system. The major factors considered were:

(i) to reduce the cost involved (i.e. find less expensive ligands).
(ii) to obtain high activity thereby allowing the reduction in catalyst loadings
(iii) to find a system for the activation of less reactive aryl halides.

Consequently there has been an increased effort in the last few years to develop more active and productive catalysts in order to use the synthetic power of Heck and related reactions for large-scale industrial applications.[1] Recently much attention has been focused on the application of palladacycles in the Heck reaction. Herrmann and Bellar *et al.* were among the first to investigate these type complexes as active catalysts.[11] It was found that cyclopalladated Pd(II) complexes are inherently air and thermally stable and act a source for the active Pd(0) species. The increased catalytic activity of palladacycles is partially due to their thermal stability in solution. Complexes such as [$Pd(PPh_3)_2(OAc)_2$] and [$Pd_2(PPh_3)_2(\mu\text{-}OAc)_2(OAc)_2$] are deactivated at temperatures above 120°C.[1] The depletion of the catalyst stabilising phosphine causes the deposition of elemental palladium (palladium black) resulting in a breakdown of the catalytic cycle. However, with the palladacycle **20** palladium deposits and phosphorus carbon bond cleavage products are not observed at temperatures up to 130°C, with the result that no yield-reducing by-products are formed.[11] Palladacycles like **20** can be used as catalysts without the addition of excess ligand and small concentrations of catalyst ($\sim 5 \times 10^{-3}$ molar) are sufficient for coupling of activated aryl bromides, while up to now much high concentrations (up to 5%) were needed.[11] This increased their attractiveness for Heck type catalysis, because they have an increased lifetime as catalysts and are particularly advantageous for less reactive substrates. However, the palladacycle **20** is synthesised from the phosphine ligand tris(2-mesityl)-phosphine, which is expensive and air sensitive. Hence this prompted us to look at the phosphite palladacycle **22** which is easily synthesised from the reaction of palladium dichloride with one equivalent of the ligand tris(2,4-di-*tert*-butylphenyl)phosphite **6** in high yield.[12] The triarylphosphite ligand **6** is commercially available and is cheaper than the conventional phosphine ligand. Ligand **6** is air and moisture stable. When all these factors are combined, the result is a catalyst that is synthesised from more robust and cheaper starting materials, which helps to reduce the costs involved.

Originally it was thought that highly donating phosphine ligands would improve the coupling of aryl chlorides and less reactive aryl bromides however there are a number of drawbacks associated with these types of ligands. It was found that these ligands could be replaced by the cheap and readily available phosphite ligands instead. Spencer described the first report of the use of phosphites as ligands as early as 1983.[10] This involved the application of triphenylphosphite as shown in scheme 2.2.



Scheme 2.2 The Heck reaction with triphenylphosphite as ligand

The results obtained (TON of 13,000 and a TOF of 1,900 h^{-1}) were comparable to those obtained with classical phosphines such as PPh_3 and P(*o*-Tol)$_3$. However, due to the weak coordination of phosphites, they make rather unstable catalysts and have remained underdeveloped until recently. Since fast deactivation of the catalyst can be overcome if phosphites are taken either in large excess, or as a preformed orthometallated palladium complex such as **22**, the reactions can be run at higher temperatures (≤130°C).[4]

This current study explores metallated phosphite complexes as active catalysts for the Heck reaction.

Complex **22** turned out to be a highly efficient catalyst for the reaction of bromoarenes with styrene or butyl acrylate (*c.f.* results and discussion section 2.3.5). Record values of TONs were observed for the reaction of 4-bromoacetophenone with butyl acrylate (up to 1, 000, 000, TOF = 166, 667 with 100% conversion) and styrene (up to 5,750,000, TOF = 83,333 with 57.5% conversion). Deactivation of catalyst due to palladium black deposition can be avoided by the addition of an extra amount of ligand tris(2,4-di-*tert*-butylphenyl)phosphites **6** (5-fold relative to palladium complex).[13]

2.3 Results and Discussion

2.3.1 Synthesis of $[\{Pd(\mu\text{-}Cl)\{P(OC_6H_2\text{-}2,6\text{-}{}^tBu_2)(OC_6H_3\text{-}2,4\text{-}{}^tBu_2)_2\}\}_2]$ complex 22

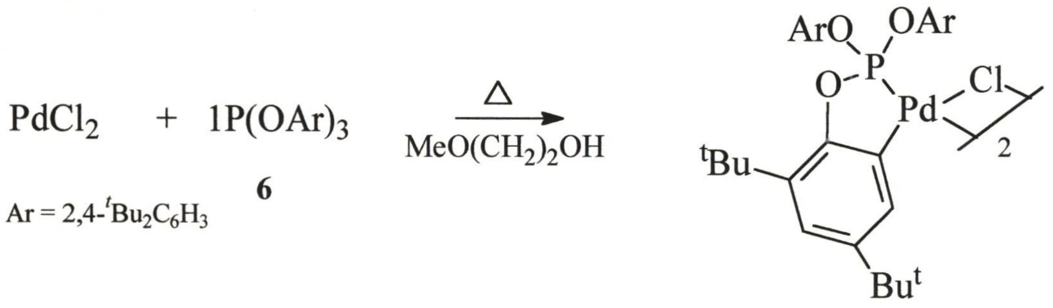
It was previously shown by our group that $PdCl_2$ reacts at room temperature with two equivalents of tris(2,4-di-*tert*-butylphenyl)phosphite **6** to produce complex **24** (scheme 2.3).[14] The ^{31}P NMR spectrum of complex **24** has only one singlet at δ 84.5 ppm. This proves that only one isomer *i.e. cis* or *trans* is formed. Conversely, the ^{31}P NMR spectrum of $[PdCl_2\{P(OC_6H_4\text{-}2\text{-}Me)_3\}_2]$ shows two singlets (δ 84.9 and 84.5 ppm respectively) indicative of a *cis/trans* mixture. This implies that complex **24** must have either a *cis* or *trans* configuration. In consideration of the steric profile of the ligand **6** one would predict a *trans* configuration for **24** and this has been confirmed by infra-red (I.R.) spectroscopy because a Pd-Cl stretch at 373 cm^{-1} was observed. This compares well with the I.R. spectrum for the *trans* configuration of $[PdCl_2\{P(OC_6H_4\text{-}2\text{-}Me)_3\}_2]$ which shows a Pd-Cl stretch at 375 cm^{-1}.[15]

$$PdCl_2 \quad + \quad \underset{6}{2P(OAr)_3} \longrightarrow \underset{24}{trans\text{-}[PdCl_2\{P(OAr)_3\}_2}$$

Ar = $2,4\text{-}{}^tBu_2C_6H_3$

Scheme 2.3 The reaction of $PdCl_2$ with a triaryl phosphite

The thermolysis of **24** in 2-methoxyethanol leads to the formation of the orthometallated palladium dimeric complex $[\{Pd(\mu\text{-}Cl)\{P(OC_6H_2\text{-}2,6\text{-}{}^tBu_2)(OC_6H_3\text{-}2,4\text{-}{}^tBu_2)_2\}\}_2]$ **22** and one equivalent of free ligand **6**.[14] A major drawback to this synthetic route is that separation of the product from **24** proves to be difficult.[14] A more convenient way to synthesise **22** is the direct reaction of one equivalent of **6** with $PdCl_2$ in 2-methoxyethanol at reflux for 2 hours.[14] As described in chapter 1 (page 28) Albinati *et al.* showed the synthesis of related cyclopalladated phosphite complexes which involved the refluxing of the monodentate phosphite complex with one equivalent of palladium dichloride in a high boiling point solvent such as toluene or xylene.[15] The formation of the dimer with only one orthometallated triarylphosphite ligand **6** on each palladium rather than the formation of the monomer with one metallated and one non-metallated **6** implies that the dissociation of the ligand **6** from the monomer $[PdCl_2\{P(OC_6H_3\text{-}2,4\text{-}^tBu_2)_3\}_2]$ is considerably more facile than that of the less bulky phosphites. This is probably attributed to the steric bulk of tris(2,4-di-*tert*-butylphenyl)phosphite. As observed with less bulky phosphite analogues of **22**, the ^{31}P NMR spectrum in $CDCl_3$ at 298 K shows the product to be a mixture of *sym-trans* and *sym-cis* isomers with two broad singlets at δ 119.2 and 118.7 ppm in an approximate 2:1 ratio respectively.[14]



Scheme 2.4 The synthesis of the metallated complex **22**

Whilst in solution a *cis/trans* mixture is observed. Only the *sym-trans* isomer is present in the solid state, which is evident from the X-ray data. The crystal structure shows that the orthometallation of the phosphite leads to the formation of a five membered ring with some ring strain observed with the coordination around the square planar palladium(II) atoms also distorted. Figure 2.1 shows the molecular structure of **22** where thermal ellipsoids are set at 50% probability. All H-atoms are omitted for clarity, as are all but the *ipso*-carbons of the non-metallated aryl rings. Three ^{t}Bu groups are disordered, only major orientation of C7-C10 shown. Selected bond distances (Å) and bond angles (°) are listed in tables 2.1 and 2.2 respectively.[12]

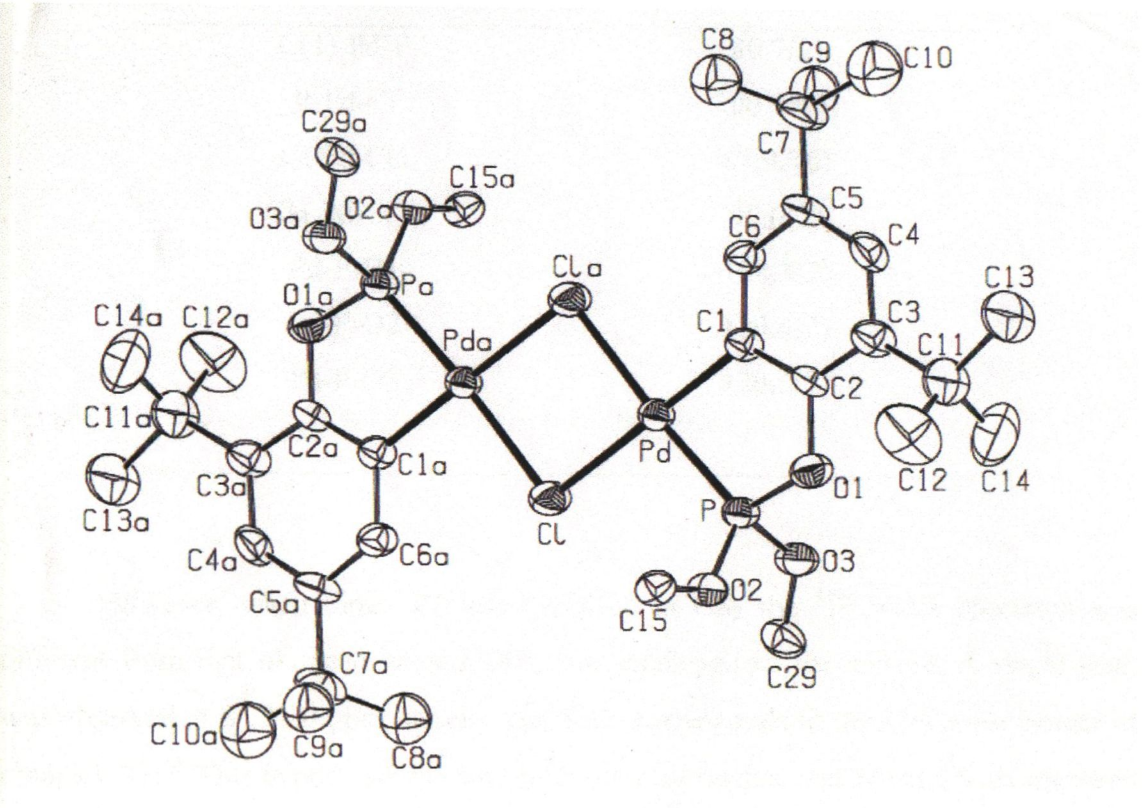


Figure 2.1 X-ray Structure of **22**

Table 2. 1 Selected bond distances (Å) for **22.**[12]

Bonds	Bond lengths (Å)
Pd-C(1)	1.998(6)
Pd-Cl	2.4180(16)
Pd-Cla	2.4073(17)
Pd-P	2.1668(17)
P-O1	1.592(4)
P-O2	1.585(4)
P-O3	1.584(4)

Table 2.2 Selected bond angles (°) for **22**.

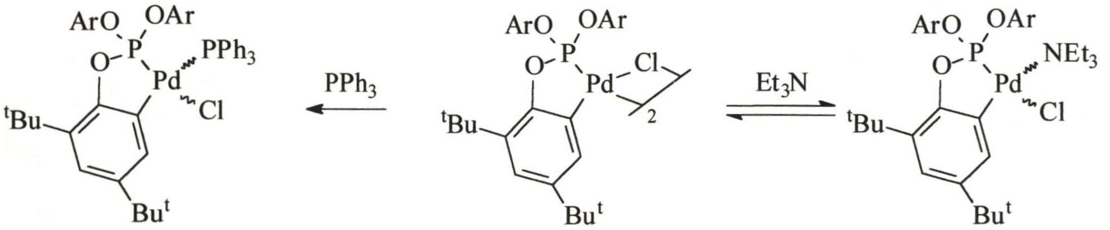
Bonds	Bond angles (°)
C(1)-Pd-P	80.7(2)
P-Pd-Cl	100.35(6)
Cl-Pd-Cla	83.92(6)
Cla-Pd-C(1)	95.0(2)
Pd-P-O1	108.3(2)
Pd-P-O2	120.4(2)
Pd-P-O3	120.6(2)

However, when dimer **22** was dissolved in CS_2 the ^{31}P NMR spectrum was different from that obtained when $CDCl_3$ was employed as the solvent. A single peak was observed at δ 121.0 ppm, which most likely corresponds to the *sym-trans* isomer of complex **22**.[14] This hypothesis fits well with the observation that when CS_2 is removed under reduced pressure and the complex re-dissolved in $CDCl_3$, the ^{31}P NMR spectrum shows two peaks with unchanged chemical shifts and the original ratio of approximately 2:1 *trans* and *cis* isomers[14] Thus the equilibrium between the *trans* and *cis* isomers can be forced to the *trans* side when the dimer **22** is dissolved in a coordinating solvent such as CS_2. However, when a non-coordinating solvent such as carbon tetrachloride was employed as solvent no change in the geometry of the dimer **22** was observed. This proves that the configuration of the dimer **22** is strongly solvent dependent.

Surprisingly, we also found that the room temperature reaction of **6** and $PdCl_2$ in a mixture of dichloromethane and ethanol also gave **22** in high yields within 2 days as a pale yellow powder. Characterisation of this compound showed that the compound achieved is identical to that achieved by the method of refluxing ligand **6** and $PdCl_2$ in 2-methoxyethanol. To the best of our knowledge this ambient temperature orthopalladation of a triarylphosphite ligand is without precedent. Presumably the facile nature of this reaction is due to the steric profile of the bulky triarylphosphite ligand, **6**. This is the first example of orthometallation of phosphite ligands occurring at room temperature. Previously the only example of metallation occurring at room temperature was for amines as described by Cope in 1968.[16]

2.3.2 Dimer Cleavage Reactions

Dinuclear palladium complexes containing bridging ligands such as Cl, Br, I, OAc, are often in two configurations in equilibrium, which is strongly solvent dependent. The isomerisation presumably takes place via bridge splitting as suggested by NMR analysis.[15] These complexes are interesting because they offer a wide range of reactions that can be conducted with appropriate ligands such as phosphines, amines, etc. to afford mononuclear complexes such as $[Pd(\mu\text{-}Cl_2)\{P(OC_6H_2\text{-}2,6\text{-}{}^tBu_2)(OC_6H_3\text{-}2,4\text{-}{}^tBu_2)_2\}_2(PPh_3)]$ **25**.[14] The tiphenylphosphine adduct **25** and triethylamine adduct **26** of the palladium dimer **22** were formed and studied (scheme 2.5).



25

22

26

$Ar = 2,4\text{-}{}^tBu_2C_6H_3$

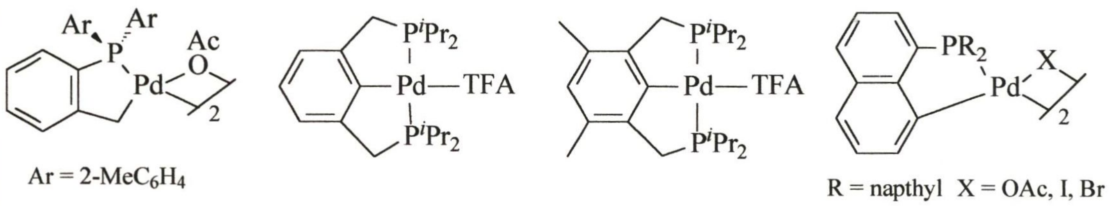
Scheme 2.6 Dimer Cleavage Reactions

The ^{31}P NMR spectrum of complex **25** revealed the formation of *trans* and *cis* isomers. The isomer in which the two phosphorus atoms are *trans* appeared as an AB system with one doublet at δ 127.9 ppm for the phosphite and another at δ 31.4 ppm for the phosphine with a large coupling of 604 Hz.[14] The isomer in which the two phosphorus atoms are *cis* appeared as an AB system with one doublet at δ 130.8 ppm and another doublet at δ 17.4 ppm which correspond to the phosphite and phosphine respectively, with a considerably smaller coupling constant of 41 Hz.[14]

When complex **22** is reacted with one equivalent of triethylamine a *cis* – *trans* mixture is formed that exists in equilibrium with the starting material. However, it was possible to force the equilibrium by employing an excess of triethylamine resulting in formation of **26**. The ^{31}P NMR spectrum of the latter shows a doublet at δ 128.16 ppm with a coupling constant of 193.4 Hz. The fact that these dimer cleavage reactions can occur relatively easily and are reversible may help in the understanding of the mechanistic route of complex **22** with in the Heck reaction.

2.3.3 Reactivity of complex 22 in the Heck reaction.

It has been previously noted by Hermann and co-workers that the use of the Pd(II) complex **20** with metallated tris(2-methylphenyl)phosphine and related compounds are highly efficient catalysts for the Heck reaction.[1] Similarly, the palladated complexes **27** and **28** have recently been shown to be active catalysts,[17] as have palladacyclic trinaphthylphosphine complexes **29**.[18]



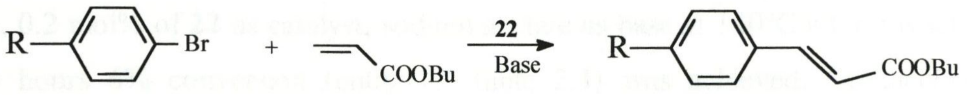
20 **27** **28** **29**

Scheme 2.10 Palladated complexes that have been used as catalysts for the Heck reaction.

This chapter describes the orthometallated palladium dimer **22** as an active catalyst for the Heck reaction obtaining very high turn over numbers (TONs). Similar to the reaction catalysed by **20**, [1,11] the rate of coupling between aryl bromide and *n*-butyl acrylate catalysed by **22** was found to depend on the nature of the aryl bromide, with a large decrease in activity occurring with electron deficient aryl bromides.

Initial investigation of the catalytic activity of **22** in the Heck reaction involved the coupling of 4-bromoacetophenone with *n*-butyl acrylate, sodium acetate as base, 0.2 mol% of **22** as catalyst at 110°C. After one hour 2% conversion was obtained (entry 1, table 2.3). When the temperature was increased by 30°C the conversion changed from 2% to 42% after one hour (entry 2, table 2.3). On a further 20°C increase of the temperature 100% conversion was obtained after just one hour, which gave TONs of 500 [mol product.(mol Pd)$^{-1}$] (entry 4, table 2.3). While taking this into consideration the catalyst concentration was decreased to a low of 0.0001 mol%, after a reaction time of one hour 5% conversion (entry 7, table 2.3) was obtained and just after 6 hours 100% conversion (entry 9, table 2.3) was achieved.

On the examination of activated electron poor aryl bromides extraordinarily high reactivity was observed for 4-bromoacetophenone as substrate, giving turnover numbers (TONs) of up to 1,000,000 [mol product.(mol Pd)$^{-1}$] in just 6 hours (entry 9, table 2.3). Whilst the previous best catalyst (Herrmann's palladacycle **20**) for this type of reaction also obtained TONs of up to 1,000,000 [mol product.(mol Pd)$^{-1}$]the reaction time was considerably longer *i.e.* 24 hours. Compared to the previous best literature result (134, 000 [mol product.(mol Pd)$^{-1}$]) from a *in situ* catalyst Pd(OAc)$_2$ and four equivalents of tris(2-methylphenyl)phosphine[7] complex **22** achieves a TON of almost ten times greater.



Scheme 2.4 The Heck reaction

Table 2.3: Heck reaction of aryl bromides with *n*-butyl acrylate and **22** as catalyst[a]

Entry	R	Catalyst (mol%)	Base	T (°C)	Time (hrs)	Conversion (%)[b]	TON
1	$COCH_3$	0.2	NaO_2CCH_3	110	1	2	10
2	$COCH_3$	0.2	NaO_2CCH_3	140	1	42	210
3	$COCH_3$	0.2	NaO_2CCH_3	140	20	100	500
4	$COCH_3$	0.2	NaO_2CCH_3	180[c]	1	100	500
5	$COCH_3$	0.2	NEt_3	140	1	0	0
6	$COCH_3$	0.2	NEt_3	180[c]	1	94	470
7	$COCH_3$	0.0001	NaO_2CCH_3	180[c]	1	5	50,000
8	$COCH_3$	0.0001	NaO_2CCH_3	180	2	24	240,000
9	$COCH_3$	0.0001	NaO_2CCH_3	180	6	100	1,000,000
10	$COCH_3$	0.2	K_2CO_3	140	1	46	230
11	$COCH_3$	0.2	K_2CO_3	140	18	100	500
12	H	0.2	NaO_2CCH_3	140	18	51	255
13	OCH_3	0.2	NaO_2CCH_3	140	10	6	30
14	OCH_3	0.2	NaO_2CCH_3	180[c]	1	14	70
15	OCH_3	0.2	NaO_2CCH_3	180	19.5	75	375
16	OCH_3	0.2	K_2CO_3	160	1	22	110
17	OCH_3	0.2	K_2CO_3	160	18	88	440
18	OCH_3	0.01[d]	K_2CO_3	160	1	23	2,300
19	OCH_3	0.01[d]	K_2CO_3	160	65	98	9,800
20	$COCH_3$	0.2	NaO_2CCH_3	140[e]	2	32	160

[a] Reaction conditions: 50 mmol aryl bromide, 70 mmol *n*-butyl acrylate, 55 mmol base, 30 ml dimethylacetamide. [b] Determined by GC and/or ^1H NMR of reaction mixture samples, based on aryl bromide. [c] Refers to temperature of the heating bath, internal temperature range ~ 160-165°C. [c] 100 mmol of *n*-butyl acrylate. [d] With 5 equivalents of tris(2,4-di-*tert*-butylphenyl)phosphite. [e] Under air

When the deactivated electron rich substrate 4-bromoanisole is used as the aryl halide, 0.2 mol% of **22** as catalyst, sodium acetate as base at 140°C after a reaction time of 10 hours 6% conversion (entry 13, table 2.3) was achieved. On increasing the temperature to 180°C, 14% conversion (entry 14, table 2.3) after a 1 hour reaction time and after 19.5 hours, 75% conversion (entry 15, table 2.3) was obtained. However, by simply changing the base from sodium acetate to potassium carbonate and at a slightly lower temperature of 160°C, 22% conversion (entry 16, table 2.3) is observed after just one hour while after 18 hours 88% conversion (entry 17, table 2.3) is reached. While optimum conversion was observed with 0.01 mol% of **22** as catalyst with five equivalents of the ligand tris(2,4-di-*tert*-butylphenyl)phosphite **6** added, after one hour 23% conversion (entry 18, table 2.3) was reached, with 98% achieved after a total of 65 hours (entry 19, table 2.3) to give TONs of up to 10,000 [mol product.(mol Pd)$^{-1}$]. This is over 100 times higher than that reported with **20**, at one-fifth the catalyst concentration.

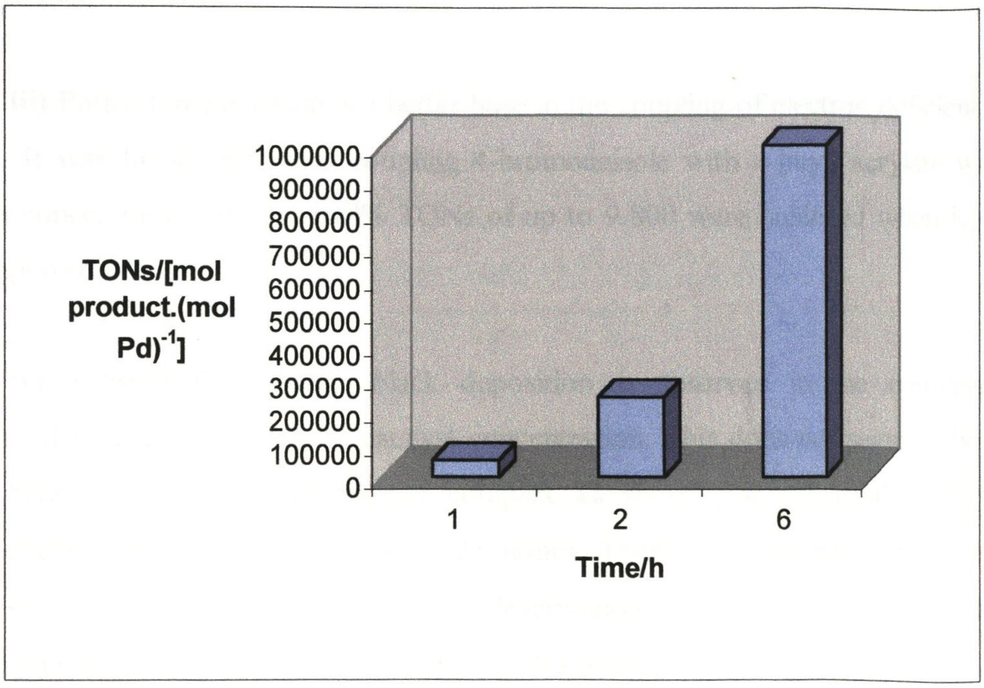
The coupling of n-butyl acrylate and bromobenzene required higher catalyst quantities (0.2 mol%). However, useful turnover numbers were also obtained for complex **22** as a TON of 255 [mol product.(mol Pd)$^{-1}$] (entry 12, table 2.3) was achieved with a reaction time of 18 hours, while a TON of 48 [mol product.(mol Pd)$^{-1}$] with complex **20** was obtained after 48 hours.

Treatment of aryl chlorides like 4-chloroacetophenone with n-butyl acrylate under standard conditions with palladacycle **22** resulted in little or no activity and was accompanied by early deposition of palladium black. As a result the use of aryl chlorides was not pursued any further at this time.

A surprising result is that complex **22** catalyses the coupling of 4-bromoacetophenone with n-butyl acrylate even under air (entry 20, table 2.3). Even though there is a decrease in the activity this result is a clear indication that this system is very robust.

The best way to visualise the catalytic activity of complex **22** is by the following graph, a plot of TONs achieved with a catalyst concentration of 0.0001 mol% versus reaction time shows the high activity clearly.

Graph 2.1 TONs Vs reaction time



2.3.4 A study of the reaction conditions

In order to determine the best reaction conditions which would yield the highest TONs for the use of palladacycle **22** in the Heck reaction, experiments were carried out using n-butyl acrylate and the activated aryl bromide, 4-bromoacetophenone as the standard coupling reaction. From the results obtained it was possible to make the following observations.

i) Catalytic activity becomes evident at approximately 110°C when sodium acetate is employed as the base and increases significantly up to a temperature of 180°C, giving TONs of up to 1,000,000 [mol product.(mol Pd)$^{-1}$] and maximum turnover frequencies (TOFs) of up to at least 190,000 [mol product.mol Pd^{-1}.h^{-1}].

ii) When triethylamine is used as the base catalytic activity is inhibited until 140°C possibly implying co-ordination of the amine as a ligand. This competes effectively with the co-ordination of the *n*-buytl acrylate or the oxidative addition of the aryl-halide therefore decreasing its activity. However, catalytic activity is resumed if the temperature is increased to 180°C. What also became clear from these studies is by simply changing the base from sodium acetate to potassium carbonate there was no great increase in activity.

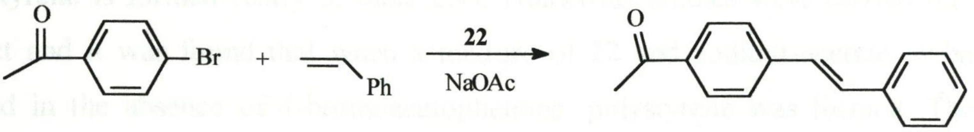
iii) Potassium carbonate is a better base in the coupling of electron deficient aryl halides. It was found that when coupling 4-bromoanisole with *n*-buytl acrylate with a catalyst concentration of 0.01 mol% TONs of up to 9,800 were achieved when K_2CO_3 was employed.

iv) Substantial palladium black deposition is observed in the coupling of deactivated bromides at 0.2mol% catalyst concentration. This does not seem to be due to the thermal decomposition because complex **22** shows good thermal stability in dimethylacetamide at 140°C even after 24 hours. Therefore it seems likely that the deposition is due to one or more catalyst deactivation pathways. Deactivation of the catalyst can be avoided by the addition of an extra amount of the ligand tris(2,4-di-*tert*-butylphenyl)phosphite **6**.

A substantial increase in activity was observed in the coupling of 4-bromoanisole and *n*-butyl acrylate when a five-fold excess of the tris(2,4-di-*tert*-butylphenyl)phosphite **6** per palladium centre is added to the catalyst.

2.3.5 Highest activity obtained with complex 22.

Simply by changing the olefin from *n*-butyl acrylate to styrene the highest activity for complex **22** in the Heck reaction was observed. The results obtained are summarised in table 2.4



Scheme 2.5 The coupling of 4-bromoacethophenone with styrene

Table 2.4: Heck reaction of aryl bromides with styrene and **22** as catalyst.[a]

Entry	Catalyst (mol%)	T (°C)	Time (hrs)	Conversion (%)[b]	TON
1	0.2	140	1	63	315
2	0.2	140	24	100	500
3	0.0001	180[c]	1	29	290,000
4	0.0001	180	21	96	960,000
5	0.00001	180[c]	69	57.5[d]	5,750,000

[a]Reaction conditions: 50 mmol aryl bromide, 70 mmol styrene, 55 mmol base, 30 ml dimethylacetamide. [b]Determined by GC and/or ^{1}H NMR of reaction mixture samples, based on aryl bromide. [c]Refers to temperature of the heating bath, internal temperature range ~ 160-165°C. [d] Substantial polystyrene formation observed.

The first step was to examine the coupling of 4-bromoacetophenone with styrene at 140°C with sodium acetate and 0.2 mol% of **22** as catalyst (entry 1, table 2.4), after one hour 63% conversion was obtained and 100% after 24 hours (entry 2, table 2.4). When lowering the catalyst concentration to 0.0001 mol%, extremely high activity for complex **22** was observed in the coupling of 4-bromoacetophenone with styrene, with 29% conversion after just one hour and 96% after 21 hours.

The system was expanded further by lowering the catalyst concentration to 0.00001 mol% this yielded 57.5% conversion after 69 hours (entry 5, table 2.4) to give TONs of up to 5,750,000 [mol product.(mol Pd)$^{-1}$]. The previous reported highest TON for any Heck reaction was 1,120,000 [mol product.(mol Pd)$^{-1}$] in the coupling of iodobenzene with methyl acrylate.[17] Although when low catalyst concentration such as 0.00001 mol% was used in the coupling of 4-bromoacetophenone and styrene some polystyrene is formed (entry 5, table 2.4). Numerous studies were carried out on this aspect and it was found that when a mixture of **22** and sodium acetate as base, was heated in the absence of 4-bromoacetophenone, polystyrene was formed. This is not surprising, because orthometallated triarylphosphite ruthenium complexes have also been shown to catalyse oligostyrene formation.[19]

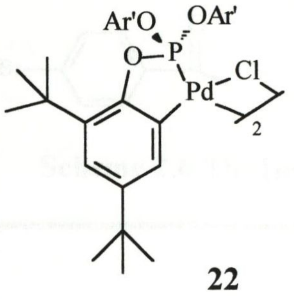
2.3.6 Synthesis of analogues of 22 complexes 15 and 25:

The palladated complex **22** reacts with triphenylphosphine in a dichloromethane/ethanol mixture to give the *cis* and *trans* isomers of **25** in 90% yield.[14] Complex **22** undergoes a bridge splitting process followed by the coordination of the triphenylphosphine ligand to give the two isomers which were revealed by ^{31}P NMR spectroscopy. In the *trans* isomer the phosphorus atoms of the phosphite and phosphine appear as an AB system with one doublet at δ 127.9 ppm for the phosphite and another at δ 31.4 ppm for the phosphine with a large coupling of 604 Hz.[14] While for the *cis* isomer the doublet of the AB system at δ 130.8 ppm for the phosphite and the doublet at δ 17.4 ppm for the phosphine has a considerably smaller coupling of 41 Hz.[14]

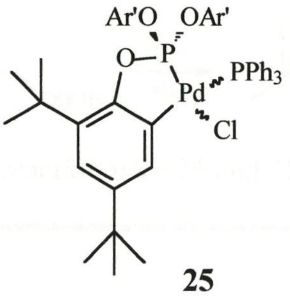
In 1968 Cope reported the reaction of N,N-dimethylbenzylamine with Pt(II) and Pd(II) chlorides to give the crystalline products di-μ-chloro-bis(N,N-dimethylbenzylamine-2-C,N)diplatinum(II) and dipalladium(II) complexes.[16] The reaction of 2 moles of N,N-dimethylbenzylamine with lithium tetrachloropalladate(II) in methanol solution for 20 hours at room temperature gave [di-μ-chloro-bis(N,N-dimethylbenzylamine-2-C,N)dipalladium] **15** in a 90% yield as a yellow crystalline solid.[16]

2.3.7 The study of the reactivity of complexes 15 and 25 in the Heck reaction.

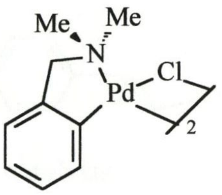
For comparative purposes, the monomeric triphenylphosphine adduct **25** of the orthometallated palladium dimer **22**, and the previously reported orthopalladated dimethylbenzylamine complex **15**[13] were tested under Heck type conditions. The results obtained are summarised in table 2.5 below.



22

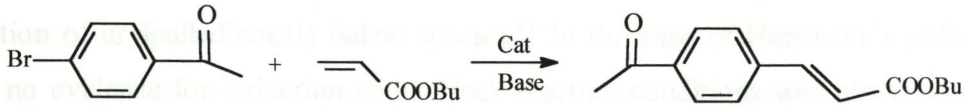


25



15

The coupling of 4-bromoacetophenone and n-butyl acrylate with 0.2 mol% of catalyst and sodium acetate as base at 140°C was the standard reaction used for this comparison experiment. The phosphine monomeric complex **25** proved to be less active than **22** with typical TONs as low as 50 (entry 3, table 2.5) and never higher than 500 (entry 4, table 2.5) even after 13 hours. This may be attributed to the deactivating influence of the triphenylphosphine. The metallated amine complex **15** proved to be at least as effective a catalyst as **22** at 0.2 mol% loading in the coupling of 4-bromoacetophenone with *n*-butyl acrylate, 53% conversion (entry 5, table 2.5) after one hour and 100% conversion (entry 6, table 2.5) after 20 hours. However, a considerable amount of palladium deposition was observed, for this reason the application of these complexes was not pursued any further at this time.



Scheme 2.6 The Heck reaction with **25** and **15** as catalysts

Table 2.5 Heck reaction of 4-bromoacetophenone and *n*-butyl acrylate with complexes **15** and **25** as catalyst.[a]

Entry	Catalyst (mol%)[c]	T (°C)	Time (hrs)	Conversion (%)[b]	TON
1	**22**	140	1	42	210
2	**22**	140	20	100	500
3	**15**	140	1	53	265
4	**15**	140	13	100	500
5	**25**	140	1	10	50
6	**25**	140	13	100	500

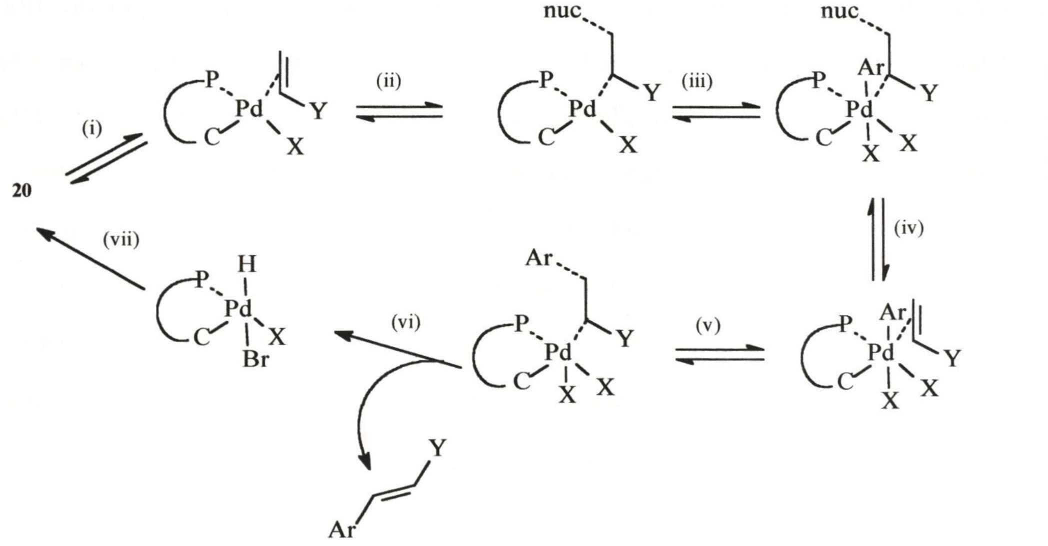
[a]Reaction conditions: 50 mmol 4-bromoacetophenone, 70 mmol n-butyl acrylate, 55 mmol sodium acetate, 30 ml dimethylacetamide. [b]Determined by GC and/or ^{1}H NMR of reaction mixture samples, based on aryl bromide. [c]Catalyst loadings of 0.2 mol %

2.3.8 Mechanistic Studies

The initial step of the Heck catalytic cycle (as describe in section 2.2) involves the reduction of Pd(II) to Pd(0) and the generation of an active species. The second step involves the oxidative addition of low-valent transition complexes to the arylhalide (R-X) bond to give $RXPdL_2$, which then loses another ligand and complexes to the alkene. After the addition of R-Pd across the carbon-carbon double bond of the alkene, β-hydride elimination and finally reductive elimination to yield the coupling product and regenerate the catalyst and the cycle starts again.[9]

The mechanism of the Heck reaction in the presence of palladacycles has not yet been fully established. It is known that the Pd(II) salts employed in catalysis are reduced by added organophosphine ligands to yield catalytically active zerovalent palladium-phosphine complexes.[20] The latter activate haloarenes by oxidative addition with the formation of arylpalladium(II) halide species.[21] In the case of Herrmann's palladacycle (Pd^{II}) no evidence for reduction under Heck reaction conditions was observed. Neither *in situ* NMR spectroscopy nor isolation of the palladacycle after successful catalysis, albeit not in quantitative yield, indicate the formation of $[Pd\{P(o\text{-}Tol)_3\}_2]$.[7a]

Herrmann and co-workers could not detect any Pd(0) in their systems and could not rule out a redox system involving a Pd(II)/Pd(IV) species but could not detect any aryl-Pd^{IV} species.[7] Shaw and co-workers proposed a new mechanism for the Heck reaction (scheme 2.9) which explained why the alkene promotes the oxidative addition of the aryl halide to the Pd(II) species.[22]



Scheme 2.9 Newly proposed mechanism for the Heck reaction according to Shaw.[22]

(i) $CH_2=CHY$

(ii) Reversible attack of nucelophile (nuc^-), attack is shown on the terminal carbon atom but it could be on the internal carbon.

(iii) Oxidative addition of aryl halide (ArX).

(iv) Reversible loss of nuc^-.

(v) Migration of aryl to terminal carbon

(vi) β-hydride elimination

(vii) Removal of HX by the base.

This newly proposed mechanism by Shaw shows that the Pd(II) metallacycle **20** is coordinated by the alkene, which then undergoes nucleophilic attack to give a σ-alkyl complex.[22] The resultant electron rich Pd(II) complex then undergoes oxidative addition with an aryl bromide to give a Pd(IV) complex. This then loses an acetate ion to regenerate coordinated alkene, after migration of the aryl from the palladium complex to the alkene. With β-hydride elimination and removal of HX (X = halide) by the base gives the desired product, ArCH=CHY, and the Pd(II) metallacycle **20**.[22]

The introduction of alkyl or aryl substituents on Pd(II) has been shown to increase the tendency towards oxidative addition. The metallacycle **20** did not react with aryl halides until the alkene is added.[7] This seems surprising at first since coordination of an alkene to Pd(II) would not be expected to increase the tendency towards oxidative addition, an important factor being back bonding from d orbitals to π^* orbitals as the alkene removes electron density from the metal. However, an alkene on coordination to a Pd(II) complex becomes susceptible to nucleophilic attack. This attack can be either *exo* or intramolecular addition of Pd-X to the coordinated carbon-carbon double bond, which results in the alkene converting to a σ-alkyl substituents.[22]

The Heck type reactions described in sections 2.2.3 - 2.3.5 are believed to work via a Pd(0)/Pd(II) redox mechanism. If starting with palladacycle **22** which is in the +II oxidation state, then a reduction step would be necessary at the start of catalysis, if no reduction occurs then the process would work via Pd(II)/Pd(IV) cycle.

2.4 Conclusion and Future work

The formation of the metallated dimeric complex **22** by the reaction of the bulky triarylphosphite ligand **6** with palladium dichloride at room temperature has been shown. The subsequent reaction of the complex with one equivalent of triphenylphosphine resulted in the splitting of the bridge to yield the monomeric complex **25**. The amine derivative **15** was prepared and used for comparative purposes. Complex **22** was employed as a catalyst for the coupling of various aryl halides with either n-butyl acrylate or styrene as the alkenes in the Heck reaction. It has high catalytic activity with turnover numbers of up to 5,750,000 (mol product.molPd^{-1}) and turnover frequencies of up to nearly 3000,000 (mol product.mol Pd^{-1}.h^{-1}).[13] The monomeric complexes **25** and **15** are similar or less active than the dimeric complex **22**. On consideration of the high thermal and air stability, this complex coupled with the cheap commercially availability of the ligand tris(2,4-di-*tert*-butylphenyl)phosphite **6** (at least two orders magnitude cheaper than the commonly used ligand tris(2-methylphenyl)phosphine) and the easy of synthesis should make these type compounds attractive for the Heck reaction.

Future work should include a full in-depth study of the reaction conditions for the Heck reaction with **22** employed as catalysts. That is to screen the catalysts with a wider range of bases and solvents, to optimise the conditions to their best. Also to explore the activity of **22** for a wider range of aryl halides, for example more sterically hindered substrates. A much more detailed look at the reaction pathway would also be desirable for a continuation of the project. A whole new project could be possible, which would be designed to examine the pathways of the catalytic cycle using NMR techniques and possible isolation and characterisation of intermediates with in the cycle.

2.5 Experimental

2.5.1 General Experimental

All chemicals were commercially available and used without further purification. DCM was distilled under nitrogen from CaH_2. Ethanol was stored over 4 Å molecular sieves. In all catalytic cases, the DMA solution was obtained in a sure-seal^{tm} bottle from the Aldrich. Stock solutions of catalyst were used on account of the low concentrations. ^1H, ^{31}P and ^{13}C NMR spectra were recorded on a DPX 400 Bruker instrument at 400, 162 and 100 MHz respectively. ^{31}P NMR spectra were referenced to a secondary external standard of PPh_3 in C_6H_6 at δ -5.5 ppm. The organic products formed by the Heck coupling reaction were determined by ^1H NMR and compared with authentic compounds. Gas chromatography analyses were performed on a Varian 3300 gas chromatography, with FID, a 20-metre capillary column and a 4290 integrator. The GC was calibrated using a calibration curve determined as a result of variation of the concentrations of samples analysed. Also by preparing and analysis of 50/50 mixtures.

2.5.2 Catalytic procedure

In a three-necked round-bottomed flask (100 ml) aryl halide (50 mmol), alkene (70 mmol), base (55 mmol), an appropriate amount of catalyst (see table 1) were suspended in DMA (30 ml) under an atmosphere of nitrogen. The reaction was stirred and refluxed at a given temperature for a given time (for more information see table 1). After the appropriate time the reaction mixture was cooled to room temperature and Et_2O (30 ml). After washing the organic layer with water and drying over $MgSO_4$ the solvents were removed by evaporation and the product analysed by ^1H NMR.

2.5.3 Gas Chromatography Analysis

Samples for GC analyses were prepared by taking 1 ml aliquots at the appropriate time during the course of the catalytic reaction. This was then filtered through a pad of celite, to remove any palladium residue. The celite is washed with Et_2O and 0.5 µL aliquots of the solution was injected and analysed by GC.

2.5.4 Synthesis of $[\{\overline{\mathrm{Pd}(\mu\text{-}\mathrm{Cl})\{\mathrm{P(OC}}{}_6\mathrm{H_2\text{-}2,6\text{-}{}^{\mathit{t}}Bu_2)(OC_6H_3\text{-}2,4\text{-}{}^{\mathit{t}}Bu_2)_2}\}\}_2]$ (22)[14]

A suspension of $\mathrm{P(OC_6H_3\text{-}2,4\text{-}{}^{\mathit{t}}Bu_2)_3}$ **6** (0.364g, 0.564 mmol) and $\mathrm{PdCl_2}$ (0.100g, 0.564 mmol) in 2-methoxyethanol (7 ml) was heated at reflux temperature for 2 hours during which time the colour changed from rust brown to pale yellow, some deposition of palladium metal was observed. The mixture was then allowed to reach room temperature and the solvent removed *in vacuo*. The residue was extracted with dichloromethane (10 ml) and the resultant solution filtered through a pad of celite. The combined dichloromethane extracts were concentrated *in vacuo* and ethanol (5 ml) was added. Subsequent concentration and addition of ethanol lead to the precipitation of product $[\{\overline{\mathrm{Pd}(\mu\text{-}\mathrm{Cl})\{\mathrm{P(OC}}{}_6\mathrm{H_2\text{-}2,6\text{-}{}^{\mathit{t}}Bu_2)(OC_6H_3\text{-}2,4\text{-}{}^{\mathit{t}}Bu_2)_2}\}\}_2]$ as pale yellow microcrystals.
Yield 0.4 g, 90%.

Sym-trans-isomer(major)

^{1}H NMR ($\mathrm{CDCl_3}$): δ 1.23 (s, 36H, *^{t}Bu*); 1.24 (s, 18H, *^{t}Bu*); 1.35 (s, 18H, *^{t}Bu*); 1.41 (s, 36H, *^{t}Bu*); 6.94 (dd, 4H, 6-free rings, $^3J_{\mathrm{HH}} = 8.5$ Hz, $^5J_{\mathrm{HH}} = 2.5$ Hz); 7.08 (s, br, 3H, *H3* or *H5*-metallated rings); 7.37 (d, 4H, *H3*-free rings $^5J_{\mathrm{HH}} = 2.4$ Hz); 7.52 d, br, 2H, *H3* of *H5*-metallated rings, $^5J_{\mathrm{HH}} = 5$ Hz) and 7.56 (d, 4H, *H5*-free rings, $^3J_{\mathrm{HH}} = 9.0$ Hz) ppm.

^{31}P-{^{1}H} NMR ($\mathrm{CDCl_3}$): δ119.2 (s, *P*OAr) ppm.

Sym-cis-isomer(minor)

^{1}H NMR ($\mathrm{CDCl_3}$): δ 1.17 (s, 18H, *^{t}Bu*); 1.21 (s, 36H, *^{t}Bu*); 1.26 (s, 36H, *^{t}Bu*); 1.34 (s, 18H, *^{t}Bu*); 7.04 (dd, 4H, 6-free rings, $^3J_{\mathrm{HH}} = 8.5$ Hz, $^5J_{\mathrm{HH}} = 2.5$ Hz); 7.12 (s, br, 2H, *H3* or *H5*-metallated rings); 7.35 (m, br, partly obscured, 4H*H3*-free rings); 7.40 (d, br, 4H, *H5*-metallated rings, $^3J_{\mathrm{HH}} = 8.5$ Hz) and 7.69 (d, br, 2H, *H3* or *H5*-metallated rings, $^5J_{\mathrm{HH}} = 7.0$ Hz) ppm.

^{31}P-{^{1}H} NMR ($\mathrm{CDCl_3}$): δ118.7 (s, *P*OAr) ppm.

2.5.5 Synthesis of $[\{Pd(\mu\text{-}Cl)\{P(OC_6H_2\text{-}2,6\text{-}^tBu_2)(OC_6H_3\text{-}2,4\text{-}^tBu_2)_2\}\}_2]$ at 298 K.

A suspension of $P(OC_6H_3\text{-}2,4\text{-}^tBu_2)_3$ (0.364g, 0.564 mmol) and $PdCl_2$ (0.100g, 0.564 mmol) in dichloromethane (5 ml) and ethanol (5 ml) was stirred at 298 K, for two days. The yellow precipitate formed was collected by filtration and the residue extracted with dichloromethane. The solvent was concentrated *in vacuo* and ethanol (5 ml) added. Subsequent concentration and addition of ethanol lead to the precipitation of product $[\{Pd(\mu\text{-}Cl)\{P(OC_6H_2\text{-}2,4\text{-}^tBu_2)(OC_6H_3\text{-}2,4\text{-}^tBu_2)_2\}\}_2]$ as pale yellow microcrystals. Yield 0.42 g, 94 %.

Analytical data as above.

2.5.6 Synthesis of $[PdCl\{P(OC_6H_2\text{-}2,6\text{-}^tBu_2)(OC_6H_3\text{-}2,4\text{-}^tBu_2)_2\}_2(PPh_3)]$ (25)[14]

A mixture of **22** (0.100 g, 0.63 mmol) and triphenylphosphine (0.033 g, 0.127 mmol) were dissolved in dichloromethane (5 ml) and ethanol (5 ml) and stirred at room temperature for fifteen minutes. The solvent was then removed *in vacuo* and the residue recrystallised from dichloromethane/ethanol.
Yield 0.12 g, 90 %.

Melting point 228-230 C

transoid-isomer:

^1H NMR ($CDCl_3$): δ 0.70 (s, 9H, *para* ^tBu orthometallated ring); 1.18 (s, 9H, *ortho* ^tBu orthometallated ring); 1.33 (s, 18H, *para* ^tBu of free rings); 1.52 (s, 18H, *ortho* ^tBu of free rings); 6.98 (t, 1H, $^5J_{HH} = 2$ Hz); 7.09 (dd, 2H, $^3J_{HH} = 2.5$ Hz, $^5J_{HH} = 2$ Hz); 7.26 (dd, 1H, $^5J = 2.5$ Hz, $^5J = 2$ Hz; 7.35 (m, br, 15H, *phenyl*) ppm.

$^{31}P\text{-}\{^1H\}$ NMR ($CDCl_3$): δ127.9 (d, *P*OAr *trans*, $^4J_{PP} = 604.1$ Hz); 31.4 (d, *P*Ph$_3$ *trans*, $^4J_{PP} = 604.1$ Hz) ppm.

cisoid-isomer:

^{1}H NMR ($CDCl_3$): δ 0.99 (s, 9H, *para ^{t}Bu* orthometallated ring); 1.30 (s, 18H, *para ^{t}Bu* of free rings); 1.31 (s, 18H, *ortho ^{t}Bu* of free rings); 1.39 (s, 9H, *ortho ^{t}Bu* orthometallated ring); 6.93 (s, br, 1H); 7.00(dd, 2H, $^3J_{HH} = 2.0$ Hz, $^5J_{HH} = 8.5$ Hz); 7.21 (d, 1H, $^5J_{HH} = 2.5$ Hz); 7.41 (m, br, 2H); 7.52 (d, 1H); 7.55 (m, 2H) and 8.48 (dt, 1H, $^3J_{HH} = 2.0$ Hz, $^5J_{HH} = 6.5$ Hz) ppm.

^{31}P-{^{1}H} NMR ($CDCl_3$): δ 130.8 (d, *P*OAr *cis*, $^4J_{PP} = 40.7$ Hz); 17.4 (d, *P*Ph$_3$ *cis*, $^4J_{PP} = 40.7$ Hz) ppm.

2.5.7 Reaction of $[\{\overline{\mathrm{Pd}(\mu\text{-Cl})\{\mathrm{P}(\mathrm{OC}}{}_6\mathrm{H}_2\text{-2,6-}{}^t\mathrm{Bu}_2)(\mathrm{OC}_6\mathrm{H}_3\text{-2,4-}{}^t\mathrm{Bu}_2)_2\}\}_2]$ with Et_3N

$[\{\overline{\mathrm{Pd}(\mu\text{-Cl})\{\mathrm{P}(\mathrm{OC}}{}_6\mathrm{H}_2\text{-2,6-}{}^t\mathrm{Bu}_2)(\mathrm{OC}_6\mathrm{H}_3\text{-2,4-}{}^t\mathrm{Bu}_2)_2\}\}_2]$ (0.01 g, 0.013 mmol) was dissolved in $CDCl_3$ in an NMR tube to this an excess of triethylamine was added. The ^{31}P NMR spectrum was recorded on this mixture.

^{31}P-{^{1}H} NMR ($CDCl_3$): δ 128.16 ppm , $J = 193.4$ Hz.

2.5.8 Synthesis of Di-μ-chloro-bis(*N,N*-dimethylbenzylamine-2,C,N)dipalladium (II) (15)[16]

Compound 15 was prepared according to literature[16] with a slight alteration only in the reaction time from 20 hrs to 15 hrs.

^{1}H NMR ($CDCl_3$) δ 2.89 (t, $J = 10.5$ Hz, NCH_3, 6H); 3.96 (q, NCH_2Ar, 2H); 6.90 (t, $J = 7.03$, ArH, 2H); 6.99 (t, $J = 7.03$, Ar*H*, 1H); 7.23 (dd, $J = 8.03$, Ar*H* 1H) ppm.

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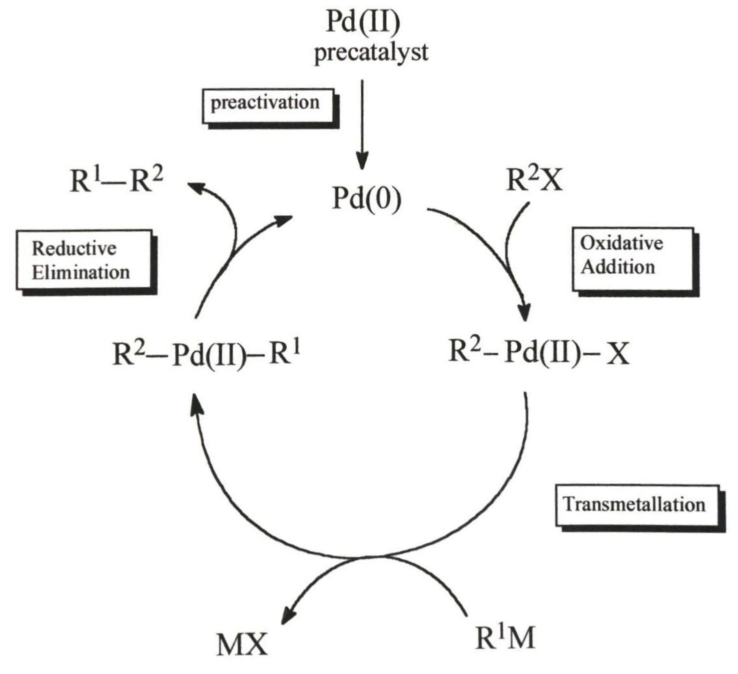
Chapter 3

Metallated Palladium Complexes as Highly Active Catalyst in the Suzuki and Stille reactions

3.1 Introduction

The palladium-catalysed Suzuki cross-coupling reaction of aryl halides and aryl triflates with arylboronic acids to form biaryls (formation of sp^2-sp^2 carbon-carbon bonds) has emerged as an extremely powerful tool in organic synthesis.[1] Compounds that contain a biaryl linkage have a diverse spectrum of applications, ranging from materials science[2] to pharmaceuticals. With respect to pharmaceuticals, the biaryl group is a key feature in the satran family of drugs for high blood pressure[3,4] and in important natural products, such as the vancomycin antibiotics.[5]

A general catalytic cycle for the cross-coupling reactions of organometallics involves an oxidative addition-transmetallation-reductive elimination sequence, as depicted in Scheme 3.1.



Scheme 3.1 Proposed catalytic cycle for cross coupling reactions

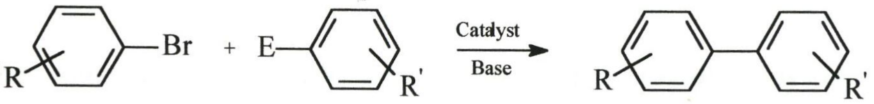
Oxidative addition of an aryl halide to a Pd(0) complex affords a stable *trans*-σ-Pd(II) complex. The oxidative addition is often the rate-determining step in a catalytic cycle. The relative reactivity decreases in the order of I > OTf > Br >> Cl. Aryl halides with electron withdrawing groups are more reactive to the oxidative addition than those with electron donating groups. A wide range of palladium complexes can be used for cross-coupling reactions with [Pd(PPh$_3$)$_4$] the most commonly used. Palladium complexes that contain fewer than four phosphine ligands or bulky phosphines are, in general, highly reactive as the formation of a coordinatively unsaturated palladium species promotes the oxidative addition step. The reductive elimination step of the organic partner reproduces the Pd(0) species, thereby allowing the process to start over again.[1] Although the mechanism of oxidative addition and reductive elimination sequences are reasonably well understood and are presumably fundamentally common processes for all cross-coupling reactions, less is known about the transmetallation step because the mechanism is highly dependent on the organometallics or reaction conditions used for the couplings.[1]

The innocuous nature of boronic acids, which are generally non-toxic and thermally, air and moisture stable, is a practical advantage of the use of Suzuki reaction in contrast to the use of other reactions.[1] Other advantages of the use of organoboron reagents in cross coupling reactions are their high selectivity and the tolerance of functional groups on either coupling partner.[6]

Similarly, the Stille cross-coupling reaction of organotin compounds with aryl iodides, bromides and triflates is a powerful synthetic tool and is a widely used method for carbon-carbon bond formation.[7] The Stille reaction is extremely versatile, it proceeds under neutral conditions and can tolerate a wide range of substituents on both coupling partners. Therefore, substituents which are not tolerated in other cross-coupling reactions, are tolerated in the Stille reaction. Also the relative low cost and accessibility of the arylstannanes is a major advantage for the use of the Stille reaction in biaryl synthesis. However, the major drawback of the Stille reaction is the toxicity of the organotin reagents and by products.[1]

3.2 Aims of Research

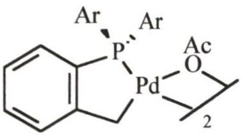
A particularly important class of C-C coupling reaction is the catalytic formation of non-symmetric biaryls (Scheme 3.2) via the coupling of aryl halides with arylboronic acids, in the Suzuki reaction, or aryltin reagents, in the Stille reaction. In general, catalyst loadings in such reactions are high (1-10 mol%) which imposes financial constraints on "scale up". Catalysts that can be used in low concentrations are a highly desirable goal. The Stille reaction sometimes requires the addition of copper(II) salts to speed up the process. Therefore the use of an active catalyst that does not require copper(II) salts for activation is also a desirable goal.



Suzuki: E = $B(OH)_2$ and Stille: E = $SnBu_3$

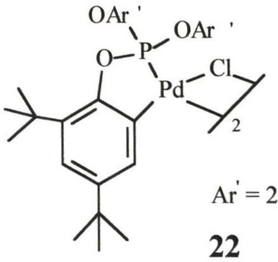
Scheme 3.2 The Suzuki and Stille coupling reactions

Recently, Beller and co-workers reported the use of the metallated [tris(2-methylphenyl)phosphinepalladium(II)] complex **20** as an efficient catalyst for the Suzuki reaction.[8] The ready ability of triarylphosphites to undergo analogous metallation coupled with the success of the metallated complex **22** in the Heck reaction prompted us to examine the possibility of the orthometallated Pd^{II}-triarylphosphite **22** complex catalysing biaryl coupling reactions, such as the Suzuki and Stille reactions.[9]



Ar = 2-MeC_6H_4

20



Ar' = 2,4-$^tBu_2C_6H_3$

22

Room temperature Suzuki couplings of aryl halides are rare and usually require toxic additives such as thallium hydroxide.[10] Hence, complex **22** will be tested for activity in the Suzuki reaction at low temperature and at room temperature.

3.3 Results and Discussion

3.3.1 Reactivity of Orthopalladated Triarylphosphite complex 22 in the Suzuki Reaction

The coupling of aryl halides and phenylboronic acid catalysed by **22** was investigated and representative results are summarised in table 3.1. In the presence of activated substrates such as 4-bromoacetophenone, extraordinarily high turnover numbers (TONs) of up to 870,000 [mol product (mol Pd)$^{-1}$] (entry 5, table 3.1) have been obtained at 110 °C after one hour. The previous highest activity with this substrate was achieved with **20** giving TONs of 74,000 at higher temperature (130°C) and much longer reaction times (16 h).[8] In the present case, the reaction was complete after just 2.25 hours giving a TON of 1,000,000 and a turnover frequencies (TOFs) of nearly 900,000 [mol product (mol Pd)$^{-1}$]. In the coupling reaction of phenylboronic acid and 4-bromoacetophenone with catalyst concentration of 0.1 mol%, it was found that lowering the temperature to 70°C lead to a reduction in activity. Nevertheless, even at 20°C high levels of activity are still observed. This is a promising result because room temperature cross coupling reactions are rare.[10]

The reaction is strongly influenced by a change of solvent or base, thus by replacing toluene with THF at 70°C there is a substantial drop in the rate of conversion. Similarly, with changing base lower rates of activity are observed. Generally less sterically hindered aryl boronic acids give better results using weak bases, whereas sterically hindered ones give higher yields with strong bases.[6] Simply by replacing K_2CO_3 with NaOAc in DMA, lower rates of conversion are observed (TON of 980 after 15 h Vs TON of 660 after 18 h).

With 4-bromobenzophenone as substrate high rates and ultimate conversions are observed. As expected, activity decreases with increasing electron density on the aryl bromide. For instance, when 4-bromoanisole is employed TOFs are about two orders of magnitude lower than 4-bromoacetophenone. However, when 4-bromoanisole is employed as substrate at a catalyst concentration of 0.001 mol% after 15 hours at 130°C, ultimate TONs of up to 30,000 were achieved. We believe these are without precedent.

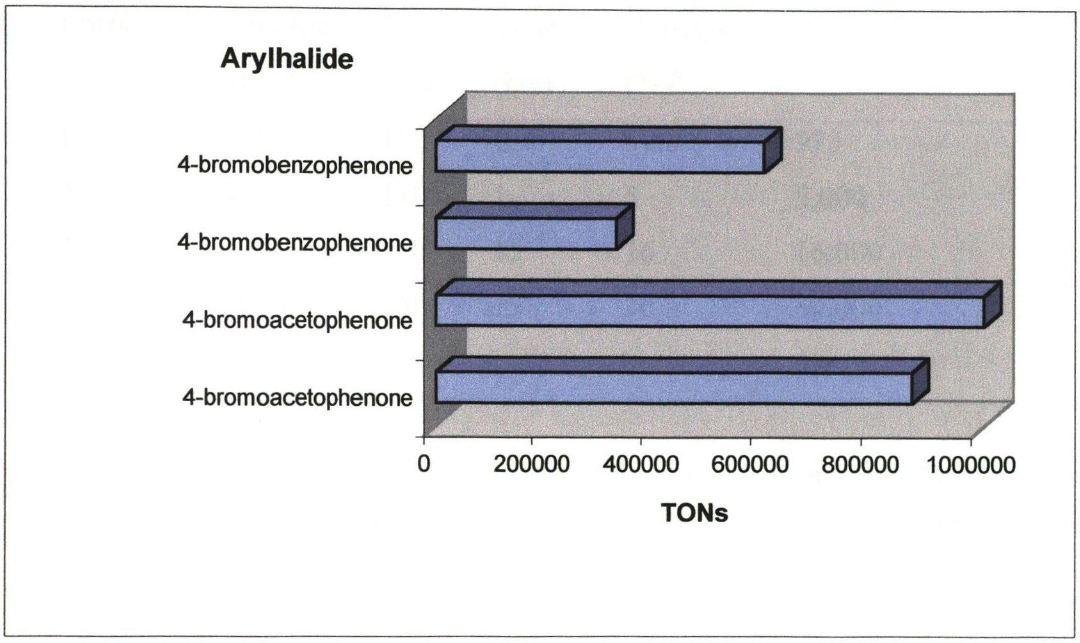
Scheme 3.1 The Suzuki coupling reaction

Table 3.1: Suzuki reaction of 4-bromoacetophenone with phenylboronic acid and **22** as catalyst.[a]

Entry	R	Solvent	Catalyst (mol%)	Base	T (°C)	Time (hrs)	Conversion (%)[b]	TON
1	$COCH_3$	DMA	0.1	NaO_2CCH_3	130	18	66	660
2	$COCH_3$	DMA	0.1	K_2CO_3	130	1	19	190
3	$COCH_3$	DMA	0.1	K_2CO_3	130	25	98	980
4	$COCH_3$	Toluene	0.1	K_2CO_3	110	1	100	1,000
5	$COCH_3$	Toluene	0.0001	K_2CO_3	110	1	87	870,000
6	$COCH_3$	Toluene	0.0001	K_2CO_3	110	2.25	100	1,000,000
7	$PhCOCH_3$	Toluene	0.0001	K_2CO_3	110	1	33	330,000
8	$PhCOCH_3$	Toluene	0.0001	K_2CO_3	110	15	60	600,000
9	$COCH_3$	Toluene	0.1	K_2CO_3	70	2	100	1,000
10	$COCH_3$	THF	0.1	K_2CO_3	70	2	20	200
11	$COCH_3$	Toluene	0.1	K_2CO_3	20	2	95	950

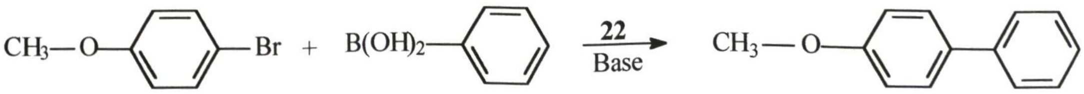
[a]Reaction conditions: 10 mmol aryl bromide, 15 mmol phenylboronic acid, 20 mmol base, 30 ml solvent. [b]Determined by GC and/or ^1H NMR of reaction mixture samples, based on aryl bromide.

Graph 3.1 Selected comparisons of TONs for two different arylhalides in the Suzuki coupling reactions



Arylhalide	Time/hours	TONs
4-bromobenzophenone	1	330,000
4-bromobenzophenone	15	600,000
4-bromoacetophenone	1	870,000
4-bromoacetophenone	2.25	100,000

The above graph 3.1 clearly shows the difference in TONs achieved when a different aryl halide is employed in the Suzuki coupling reaction with **22** as catalyst. This is an effective way for visualising the reactivity for the catalyst.



Scheme 3.2 The coupling of 4-bromoanisole with phenylboronic acid with **22** as catalyst.

Table 3.2: Suzuki reaction of 4-bromoanisole with phenylboronic acid and **22** as catalyst.[a]

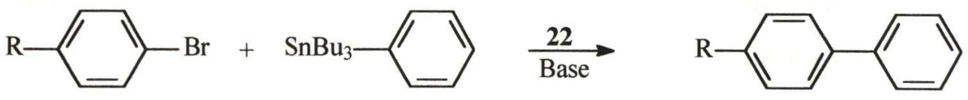
Entry	Catalyst (mol%)	T (°C)	Time (hrs)	Conversion (%)[b]	TON
1	0.1	110	1	97.5	975
2	0.001	110	1	5	5,000
3	0.001	110	15	16	16,000
4	0.001	130	15	30	30,000

[a]Reaction conditions: 10 mmol aryl bromide, 15 mmol phenylboronic acid, 20 mmol base, 30 ml solvent. [b]Determined by GC and/or ^{1}H NMR of reaction mixture samples, based on aryl bromide.

Changing to 4-chloroacetophenone as substrate leads to a considerable reduction in activity when compared to 4-bromoacetophenone, with a turnover number of 40 obtained after 20 hours at 0.2 mol% catalyst. As with the aryl bromide coupling reactions, at higher catalyst concentrations (≥0.1 mol %) deposition of palladium metal is observed. For instance, in the case of the 4-chloroacetophenone, deposited palladium does not seem to be catalytically active as samples taken at one hour show very similar conversions to those taken at 20 hours. Increasing the temperature in this reaction to 130° C did not lead to an increase in activity. The low reactivity of aryl chlorides in cross-coupling reactions is generally ascribed to their reluctance to undergo oxidative addition to Pd(0). It has been shown that aryl halides that bear an electron-withdrawing group oxidatively add to Pd(0) more readily than the corresponding unsubstituted aryl halides.[11] Due to the fact that aryl chlorides are readily available and are inexpensive it is a desirable goal to develop a catalyst and a catalytic system which would give high TONs and TOFs in Suzuki type reactions.

3.3.2 Reactivity of Orthopalladated Triaryltphosphite complex 22 in the Stille Reactions

Encouraged by the results obtained in the Suzuki reaction (section 3.3.1) the activity of complex **22** was investigated in the Stille reaction. Representative results for the coupling of tributylphenyltin with arylbromides are summarised in table 3.3. With 4-bromoacetophenone as substrate, reasonable activity in toluene is observed at 100 °C, however increasing the temperature to 120 °C leads to TONs of up to 840,000 within 18 hours. To the best of our knowledge this is the highest reported activity to date and is far superior to **20** which gives a TON of 1650 in the coupling of 4-bromoacetophenone with $PhSnMe_3$ under identical conditions.[12] As expected the reaction is not as good with electron rich bromoarenes such as 4-bromoanisole, but useful conversions (TON of 840) are still obtained.



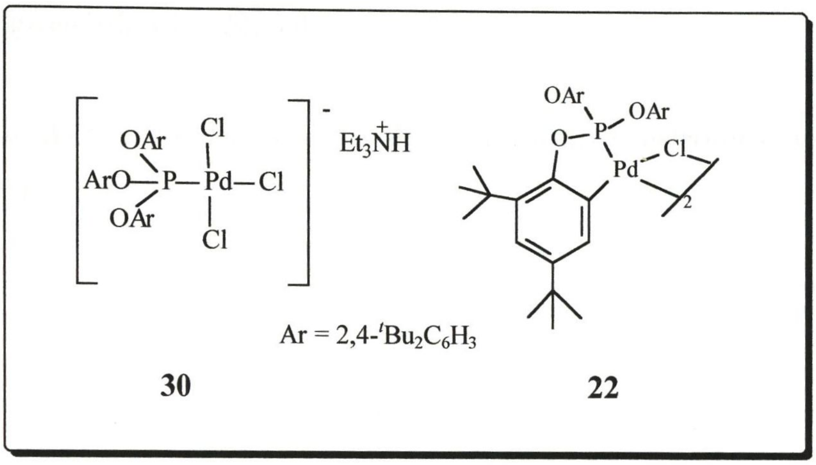
Scheme 3.3 The Stille coupling reaction catalyst by **22**

Table 3.3 Stille coupling of aryl bromides with $PhSnBu_3$ catalysed by **22**.

Entry	R	Catalyst (mol%)	T (°C)	Time (hrs)	Conversion (%)^b	TON
1	$COCH_3$	0.2	100	17.5	54	270
2	$COCH_3$	0.2	120	15	100	500
3	$COCH_3$	0.0001	120	18	83	830,000
4	OCH_3	0.1	120	15	84	840

^{a}Reaction conditions: 10 mmol aryl bromide, 15 mmol phenylboronic acid, 20 mmol base, 30 ml solvent. ^{b}Determined by GC and/or ^{1}H NMR of reaction mixture samples, based on aryl bromide.

3.3.3 Synthesis of the triarylphosphite palladium anion $[Pd\{P(OC_6H_3\text{-}2,4\text{-}Bu^t_2)_3\}_2Cl_3][Et_3NH]$ complex (30)



$Ar = 2,4\text{-}^tBu_2C_6H_3$

30

22

With increased speculation as to the mechanistic pathway of palladium(II) metallacycles in carbon-carbon bond formation the synthesis and characterisation of a palladium anion species is described here. The reaction of palladium dichloride with triethylamine hydrochloride and one equivalent of tris(2,4-di-*t*-butylphenylphosphite) **6** in dichloromethane failed to yield the desired product. Therefore, the following method was adopted and the product was obtained in excellent yield. Palladium dichloride and one equivalent of triethylamine hydrochloride were stirred together in dichloromethane for 15 minutes and to this one equivalent of tris(2,4-di-*t*-butylphenylphosphite) **6** was added. The mixture stirred for a further hour during which time the solution changed to a rust brown/orange colour. The solvent was removed and complex **30** obtained in 95 % yield after recrystallisation from a dichloromethane/hexane mixture. The ^{31}P NMR of **30** showed a singlet at δ 76.03 ppm. This value is at lower field than that achieved for coordinated tris(2,4-di-*t*-butylphenylphosphite) **6** at a metal centre, however the presence of the extra chloride ion on the metal centre would account for the shielding of the phosphorus atom and therefore the shift up-field for the phosphite peak in the ^{31}P NMR. Fine yellow crystals were obtained from the NMR solution which was layered with hexane, however these crystals proved unfruitful in the X-ray data collection.

3.3.4 The study of the reactivity of 30 in the Suzuki reaction.

The reactivity of complex **30** was tested in the Suzuki reaction and the results obtained are given below in table 3.4

Table 3.4 Suzuki coupling reaction of arylbromides with phenylboronic acid and **30** as catalyst.[a]

Entry	R	Catalyst (mol%)	Time (h)	T (°C)	Conversion (%)[b]	TON
1	4-bromoacetophenone	0.1	18	130	100	1,000
2	4-bromoacetophenone	0.0001	18	130	48	480,000
3	4-bromoanisole	0.001	18	130	36	36,000
4	4-chloroacetophenone	0.1	18	130	8	80
5	4-chloroanisole	0.1	18	130	1	10

[a]Reaction conditions: 1.0 mmol aryl bromide, 1.5 mmol phenylboronic acid, 2.0 mmol base, 5.0 ml solvent. [b]Determined by GC, based on aryl bromide.

Initial investigation of the catalytic activity of **30** in the Suzuki reaction involved the coupling of the activated electron poor substrate, 4-bromoacetophenone with phenylboronic acid, potassium carbonate as base and 0.1 mol% of **30** as catalyst at 130°C. After a reaction time of 18 hours, 100 % conversion was obtained (entry 1, table 3.4). On lowering the catalyst concentration to 0.0001 mol% under the same conditions 48% conversion was achieved after 18 hours (entry 2, table 3.4). This is a lot slower than for the same reaction when **22** was employed as catalyst which gave 100% conversion in under than two and a half hours at a lower temperature of 110°C. This may be attributed to the fact that complex **30** may act as a resting state in the catalytic cycle when complex **22** was used as catalyst. This may account for the lower activity of **30** as a coupling catalyst.

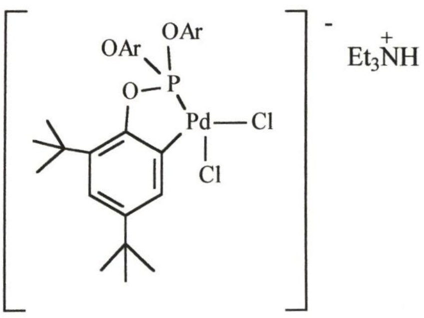
Surprisingly, when the deactivated electron rich substrate 4-bromoanisole is used as the aryl bromide, 0.001 mol% of **30** as catalyst under the same conditions 36% conversion was obtained after 18 hours. This is higher than that obtained with **22** (30%

conversion after 15 hrs, entry 4 table 3.2) as catalyst albeit with a slightly longer reaction time. This result encourages the use of an anion species such as **30** in the coupling of deactivated aryl bromides in the Suzuki coupling reaction.

When the aryl chlorides such as 4-chloroacetophenone and 4-chloroanisole were tested with **30** as catalyst, little activity was observed even after long reaction times. This activity was similar to that of **22** with aryl chlorides.

3.3.5 Attempted synthesis of the metallated analogue of (30)

Several attempts were made to synthesise the metallated analogue of **30**. The first attempt was to react the metallated dimer **22** and triethylamine hydrochloride together in dichloromethane at room temperature overnight. When the solvent was removed and a ^{31}P NMR of the crude product was obtained it revealed that no reaction had occurred.



Ar = 2,4-^{t}Bu$_2$C$_6$H$_3$

31

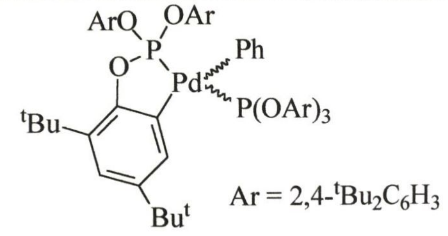
The second attempt involved refluxing **30** in toluene overnight. Again this was unsuccessful as determined by the ^{31}P NMR, which showed three peaks. Two singlets at δ 120 and 119 ppm that correspond to the peaks for the metallated dimer **22** and a third peak appearing at δ 123.2 ppm, which most likely corresponds to the metallated analogue of **30**.

A third attempt was to react the palladium dimer **22** with two equivalents of tetra-*n*-butylammonium chloride in toluene at reflux temperature over night. Again this gave a mixture of the starting dimer and the desired complex **31** in approximately 85% product 15% starting material ratio.

Finally when an excess of tetra-*n*-butylammonium chloride was refluxed with the dimer **22** the ^{31}P NMR showed just a singlet at δ 123.2 ppm but the ^{1}H NMR spectra showed a mixture of the metallated anion product and tetra-*n*-butylammonium chloride. Several attempts to separate this mixture failed to give the desired product. The work was halted due to time constraints.

3.3.6 Study of the Mechanism Involved in Catalytic Reactions

Whilst the precise mechanism of Heck type reactions in the presence of palladacycles has not been established, it is known that the Pd(II) salts are reduced by organophosphine ligands to yield catalytically active zerovalent palladium-phosphine complexes.[11] The latter activate haloarenes by oxidative addition with the formation or an arylpalladium(II) halide species.[13] Therefore we suspect a similar pathway occurs for the coupling reactions studied in this report. In order to prove this we are currently undertaking mechanistic studies. Initial research has concentrated on the mechanistic side of the Suzuki reaction, as catalytic activity is evident at room temperature and allows us to look at NMR experiments. Unfortunately the reaction of complex **22** with one equivalent of $PhB(OH)_2$ and K_2CO_3 in the absence of an aryl bromide leads to palladium deposition.



32 *trans*(major) *cis*(minor)

However, when this reaction was monitored in the presence of one equivalent of tris(2,4-di-*tert*-butylphenyl)phosphite **6**, decomposition was inhibited and it was possible to monitor the reaction by ^{31}P NMR spectroscopy. The spectrum after 30 minutes consisted mainly of a mixture of free ligand **6** and the orthometallated palladium dimeric complex **22**. Amongst some minor peaks also evident are two relatively major low field double doublets.

Tentative assignment of these two peaks is to the presence of two isomers of $[\mathrm{Pd}\{\mathrm{P(OC_6H_2\text{-}2,6\text{-}Bu^t_2)(OC_6H_3\text{-}2,4\text{-}Bu^t_2)_2}\}\{\mathrm{P(OC_6H_3\text{-}2,4\text{-}Bu^t_2)_3}\}(\mathrm{Ph})]$ **32**, in which the P atoms are disposed *trans* (major) or *cis* (minor). There is a small peak at –18.0 ppm. Such a high field shift is consistent with the formation of a Pd(0)-phosphite complex. We postulate that reductive elimination of the orthometallated phosphite aryl and a phenyl group occurs, yielding a catalytically active palladium species. This is in accord with findings for the use of Hermann's complex **20** in the Stille reaction.[8] However, a Pd(II)/Pd(IV) couple has recently been suggested to be active in the Heck arylation of alkenes catalysed by **20** and related complexes[14,15] and at this stage we cannot rule out a related pathway.

3.4 Conclusion

In summary, the orthopalladated complex **22** proves to be an extremely active catalyst in biaryl coupling reactions. Turnover numbers of up to 1,000,000 (mol product.mol Pd^{-1}) and turnover frequencies of nearly 900,000 (mol product.mol $Pd^{-1}.h^{-1}$) were achieved in the Suzuki reaction and turnover numbers of up to 840,000 (mol product.mol Pd^{-1}) in the Stille reaction. The palladated complex **22** showed reasonable catalytic activity in the Suzuki coupling reaction at room temperature. In view of this high activity and the possibility of room temperature catalysis when **22** is employed as catalyst for the Suzuki reaction and the easy of synthesis of the palladated complex **22** adds to the attractiveness of **22** as a catalysts for biaryl coupling reactions.

The possibility of palladium anion complexes **30** and **31** as a catalyst in cross coupling reactions was also explored in this chapter.

Future work should involve the continued study of complex **22** as catalyst in biaryl coupling reactions with particular emphasis on room temperature reactions. Studies should be carried out using sterically hindered substrates and the more inactive aryl chlorides. Also a further in-depth study of the anionic complex **30** in biaryl coupling reactions would be a desirable goal. Likewise the successful synthesis and isolation of the metallated derivative of **30**, **31** with investigation of its activity as a catalyst in biaryl coupling reactions such as Suzuki and Stille reactions.

Mechanistic studies have given some insight into the pathway in which complex **22** under takes in the Suzuki coupling reactions. These are just preliminary results and a more in depth study is recommended for future work.

As a result of this high activity achieved with **22** future studies should also involve the investigation of similar metallated palladium complexes, which are also reported in this thesis see chapter 5.

3.5 Experimental

3.5.1 General Experimental

All chemicals were commercially available and used without further purification. Toluene was freshly distilled under nitrogen from a sodium/benzophenone ketyl. DCM was distilled under nitrogen from CaH_2. Ethanol was stored over 4 Å molecular sieves. The DMA solution was obtained in a sure-seal^{tm} bottle from the Aldrich Chemical Company. Stock solutions of catalyst were used on account of the low concentrations. Tetra-*n*-butylammonium chloride was obtained from Aldrich Chemical Company in a sealed vial this was opened under in an inert atmosphere and store in a Schlenk under nitrogen. ^1H, ^{31}P and ^{13}C NMR spectra were recorded on a DPX 400 Bruker instrument at 400, 162 and 100 MHz respectively. ^{31}P NMR spectra were referenced to a secondary external standard of PPh_3 in C_6H_6 at δ -5.5 ppm. The organic products formed by the Suzuki coupling reaction were determined by ^1H NMR and compared with authentic compounds. Gas chromatography analyses were performed on a Varian 3300 gas chromatograph, with FID, a 20-metre capillary column and a 4290 integrator.

3.5.2 Catalytic procedure

In a three-necked round-bottomed flask (100 ml) aryl halide (10 mmol), phenylboronic acid (15 mmol), base (20 mmol), an appropriate amount of catalyst were suspended in solvent (30 ml) (see tables 3.1, 3.2, 3.3 and 3.4) under an atmosphere of nitrogen. The reaction was stirred and refluxed at a set temperature for a set time (for more information see tables 3.1, 3.2, 3.3 and 3.4). After the appropriate time the reaction mixture was cooled to room temperature and Et_2O (30 ml). After washing the organic layer with water and drying over $MgSO_4$ the solvents were removed by evaporation in air and the product analysed by ^1H NMR.

3.5.3 Gas Chromatography Analysis

Samples for GC analyses were prepared by taking 1 ml aliquots at an appropriate time during the course of the catalytic reaction. This was then filtered through a pad of celite, to remove any palladium residue. The celite is washed with Et_2O and 0.5 μL aliquots of the solution was injected and analysed by GC.

3.5.4 Synthesis of $[Pd\{P(OC_6H_3\text{-}2,4\text{-}Bu^t_2)_3\}_2Cl_3][Et_3NH]$ (30)

A mixture of palladium dichloride (0.10 g, 0.56 mmol) and triethylamine hydrochloride (0.078 g, 0.56 mmol) were stirred together at room temperature for 15 minutes. To this mixture tris(2,4-di-*t*-butylphenylphosphite) (0.36 g, 0.56 mmol) was added and the mixture was stirred for an hour. During which time the solution changes from a pale yellow to a rust brown colour. The solvent was removed *in vacuo* and the residue recrystallised form a dichloromethane/hexane mix to yield the product as a fine orange powder in 95% yield.

^1H NMR ($CDCl_3$): δ 1.28 (s, 27H, *para* ^{t}*Bu* aryl ring); 1.40 (t, *CH_3*, Et_3N); 1.52 (s, 27H, *ortho* ^{t}*Bu* aryl ring); 3.08 (q, *CH_2*, Et_3N); 7.1 (d, *H*-aryl, J = 9 Hz); 7.34 (s, *H*-aryl); 7.99 (d, *H*-aryl, J = 9 Hz) ppm.

^{13}C NMR ($CDCl_3$): δ 8.1 (s, *CH_3*, Et_3N); 30.16 (s, *CH_3* ^{t}Bu); 34.7 (s, *C*$(CH_3)_3$, ^{t}Bu); 45 (s, *CH_2*, Et_3N) 118.8 – 124.1 aromatic carbon; 145.8 (s, *C*-aryl) ppm.

$^{31}P\text{-}\{^1H\}$ NMR ($CDCl_3$): δ 76.03 ppm.

3.5.5 Attempted synthesis of $[Pd\{P(OC_6H_2\text{-}2,6\text{-}Bu^t_2)\{(OC_6H_3\text{-}2,4\text{-}Bu^t_2)_3\}_2Cl_3][Et_3NH]$ (31)

A solution of $[\{Pd(\mu\text{-}Cl)\{P(OC_6H_2\text{-}2,6\text{-}{}^tBu_2)(OC_6H_3\text{-}2,4\text{-}{}^tBu_2)_2\}\}_2]$ (0.20 g, 0.126 mmol) and triethylamine hydrochloride (0.017 g, 0.126 mmol) in dichloromethane (10 mls) was stirred overnight at room temperature. The solvent was removed *in vacuo* and a ^{31}P NMR of the residue was obtained. This revealed that the residue was the starting dimer $[\{Pd(\mu\text{-}Cl)\{P(OC_6H_2\text{-}2,6\text{-}{}^tBu_2)(OC_6H_3\text{-}2,4\text{-}{}^tBu_2)_2\}\}_2]$.

3.5.6 Attempted synthesis of (31)

$[Pd\{P(OC_6H_3\text{-}2,4\text{-}Bu^t_2)_3\}_2Cl_3][Et_3NH]$ (0.1 g, 0.1 mmol) was dissolved in toluene (10 mls) and heated to reflux overnight. The mixture was cooled and the solvent removed *in vacuo* and a NMR obtained. The ^{31}P NMR spectra showed three peaks, two of which correspond to the dimeric complex **22** and the third peak corresponding to the desired product at δ123.2 ppm. Attempts to separate these products failed.

3.5.7 Attempted synthesis of 31 from the reaction of 22 and Bu_4NCl

A solution of $[\{Pd(\mu\text{-}Cl)\{P(OC_6H_2\text{-}2,6\text{-}{}^tBu_2)(OC_6H_3\text{-}2,4\text{-}{}^tBu_2)_2\}\}_2]$ (0.1 g, 0.127 mmol) and tetrabutylammonium chloride (0.071 g, 0.25 mmol) was refluxed in toluene (10 mls) overnight. The mixture was allowed to cool, the solvent was removed *in vacuo*, and a NMR obtained of the crude product. The ^{31}P NMR revealed a mixture again of the starting dimer **22** and the desired product **31**.

^{31}P-{^{1}H} NMR ($CDCl_3$): δ 120.3, 119.8 (*cis/trans* mixture of **22**), 124.0 ppm (metallated phosphite)

3.5.8 Attempted synthesis of 31 from the reaction of 22 and excess Bu_4NCl

A solution of $[\{Pd(\mu\text{-}Cl)\{P(OC_6H_2\text{-}2,6\text{-}{}^tBu_2)(OC_6H_3\text{-}2,4\text{-}{}^tBu_2)_2\}\}_2]$ (0.1 g, 0.127 mmol) and tetrabutylammonium chloride (0.105 g, 0.381 mmol) was stirred at room temperature in dichloromethane (10 mls) overnight. The solvent was removed *in vacuo*, and a NMR obtained of the crude product. The ^{31}P NMR revealed a singlet at δ 124.0 ppm, which corresponds to the desired product **31**. The ^{1}H NMR showed a mixture of the product and unreacted Bu_4NCl. All attempts to purify the product failed.

^{31}P-{^{1}H} NMR ($CDCl_3$): δ 124.0 ppm.

3.5.9 Formation of [Pd(P(OC_6H_2-2,6-Bu^t_2)(OC_6H_3-2,4-Bu^t_2)$_2$}{ Ph)}{P(OC_6H_3-2,4-Bu^t_2)$_3$}] (32)

A mixture of [{Pd(μ-Cl){P(OC_6H_2-2,6-^{t}Bu_2)(OC_6H_3-2,4-^{t}Bu_2)$_2$}}$_2$] (0.15 g, 0.19 mmol), phenylboronic acid (0.023 g, 0.19 mmol) and potassium carbonate (0.026 g, 0.19 mmol) were dissolved in toluene. After 30 minutes a ^{31}P NMR spectrum was recorded on this mixture.

^{31}P-{^{1}H} NMR (CDCl$_3$): δ –18.3 (s,Pd(0)OAr); 155.2 (d, *P*OAr, Non-metallated, ^2J = 29.8 Hz, *cis*-minor); 118.1 (d, *P*OAr, metallated, ^2J = 29.8 Hz, *cis*); 141.4 (d, *P*OAr, Non-metallated, ^2J = 868.4 Hz, *trans*-major); 117.3 (d, *P*OAr, metallated, ^2J = 868.4 Hz, *trans*-major) ppm.

3.6 References

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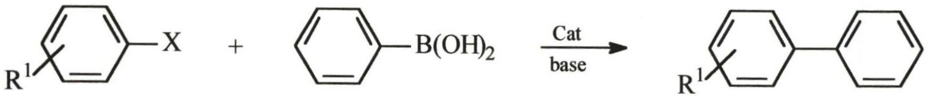
Chapter 4

Palladium bis(phosphinite) 'PCP'-pincer Complexes and their application as catalysts in the Suzuki reaction

4.1 Introduction

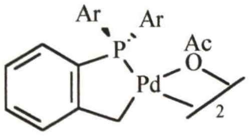
Palladium catalysed Suzuki coupling reactions (scheme 4.1) generally require fairly high catalyst concentrations, limiting their attractiveness to large-scale commercial applications. This is due to technical problems and costs associated with removal of the spent palladium from the products.



X = Br, Cl

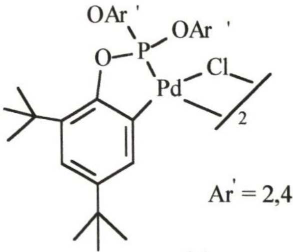
Scheme 4.1 Suzuki biaryl coupling reaction

Consequently, there has recently been much interest in developing high-activity catalysts that can be used in very low concentrations. Beller and co-workers reported the use of the palladcyclic complex **20**,[1] formed by the metallation of tris(2-tolyl)phosphine, as an efficient catalyst for the Suzuki reaction.[2] Chapter 3 describes in detail the use of the related palladated triarylphosphite complex and it was found that complex **22** shows extremely high activity with both electronically activated and deactivated aryl bromides, considerably higher than the activity reported for **20**.[3]



Ar = 2-MeC_6H_4

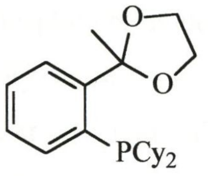
20



Ar' = 2,4-$^tBu_2C_6H_3$

22

Since then Fu and co-workers,[4] as well as Guram *et al.*,[5] have reported good, and Buchwald *et al.*[6] excellent, activity in the Suzuki reaction using palladium catalysts with the phosphine ligands PBu^t_3, **33** and **34**, respectively. However, the major drawback of these catalyst systems is that the phosphine ligands are comparatively difficult to make or are rather expensive, considerably more expensive than the palladium precursors.[7]



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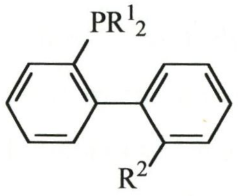


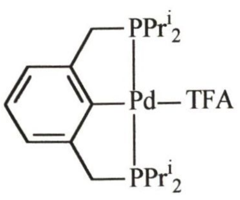
34

R^1 = Cy, Bu^t
R^2 = H, Me, Pr^i, NMe_2

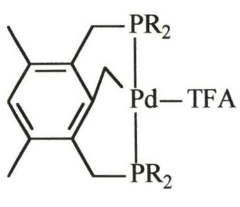
Jensen and co-workers have shown that the Iridium 'PCP'-pincer complex $IrH_2\{C_6H_3\text{-}2,6\text{-}(PBu^t_2)_2\}$ to be an efficient and robust catalyst for the dehydrogenation of a variety of aliphatic C-H bonds.[8] Milstein and co-workers have reported catalysis of the Heck reaction with aryl chlorides using electron-rich trigonal bisphosphine palladium(0) complexes.[9] These reactions exhibited a remarkable chelate effect and enable Heck coupling under milder conditions in absence of base.[9c] As a result of this they investigated the use of tridentate 'PCP'-pincer type complexes in the Heck vinylation of aryl iodides and bromides and obtained high turnover numbers using $Pd\{OC(O)CF_3\}\{C_6H_3\text{-}2,6\text{-}(CH_2PPr^i_2)_2\}$ **35a** and $Pd\{OC(O)CF_3\}\{C_6H\text{-}1\text{-}CH_2\text{-}2,6(CH_2PR_2)_2\text{-}3,5\text{-}(CH_3)_2\}$ (R = Pr^i, Bu^t) **35b**.[10]

4.2 Aims of Research

In view of the high activity that was achieved with catalysts derived from inexpensive, easily synthesised ligand sets such as triarylphosphite ligand tris(2,4-di-*tert*-butylphenyl)phosphite **6**, as described in chapters 2 and 3, this chapter explores the possibility of activity by other ligand sets. Inspired by the observations of Milstein *et al.*[10] and Shibasaki *et al.*[11] that palladated bis(phosphine) tridentate 'PCP'-complexes of type **35a, 35b** and bis(phosphite) 'PCP'-complexes of type **36** show very high activity in the Heck reaction. Milstein described that the stabilising tridentate 'PCP' ligand system, the complexes **35a** and **35b** are extraordinarily thermally stable and show no decomposition at temperatures up to 180°C.[10] The Pd(II) species, **35a**, **35b** and **36** which have a tridentate 'PCP'-ligand system which are oxygen and moisture stable. Furthermore, no catalyst degradation was observed during prolonged heating at 140 °C under typical Heck reaction conditions.[10] The utility of **35b** was demonstrated in the Heck coupling of bromobenzene with methyl acrylate which is catalysed with 3.5 x 10^{-5} mol% of **35b** to produce methyl cinnamate in 93% yield.[10] The major theme, which is associated with these systems, is the stabilisation of the active catalyst by either ligand chelation or by sterically hindering the metal centre.

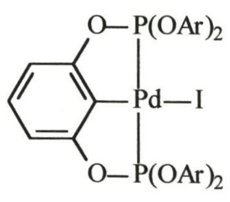


35a



R = Pr^i, Bu^t

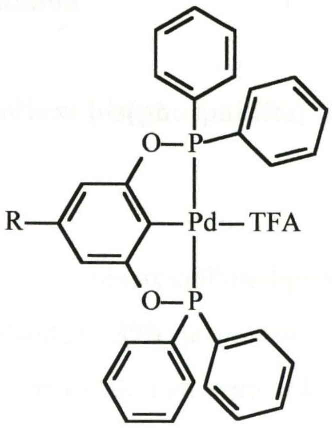
35b



Ar = 4-$MeOC_6H_4$

36

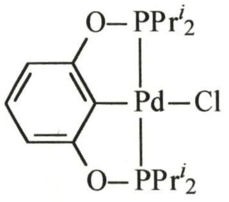
However, Milsteins 'PCP'-pincer phosphine complexes **35a** and **35b** proved to be inactive in the coupling of difficult aryl halides (i.e. aryl chlorides) this prompted us to investigate the activity of related bis(phosphinite) 'PCP'-pincer complexes $Pd\{OC(O)CF_3\}\{C_6H_3\text{-}2,6\text{-}(OPPh_2)_2\}$ **37a** and $Pd\{OC(O)CF_3\}\{C_6H_2\text{-}4\text{-}CH_3\text{-}2,6\text{-}(OPPh_2)_2\}$ **37b** in the Suzuki biaryl coupling reactions of deactivated and sterically hindered aryl halides.[12]



37a R = H
37b R = Me

The electron withdrawing nature of the alkoxy groups of the aromatic diol bound to the phosphorus atoms coupled with the tridentate chelate effect of the ligands, complexes **37a** and **37b** should prove as active catalysts in carbon-carbon bond formation reactions.

During the course of this work Jensen and co-workers reported the synthesis and catalytic activity in the Heck reaction of the isopropyl analogue $[PdCl\{C_6H_3\text{-}2,6\text{-}(OPPr^i_2)_2\}]$ **38** of compound **37a** and found them to be active catalysts in the Heck coupling reaction.[13,14]

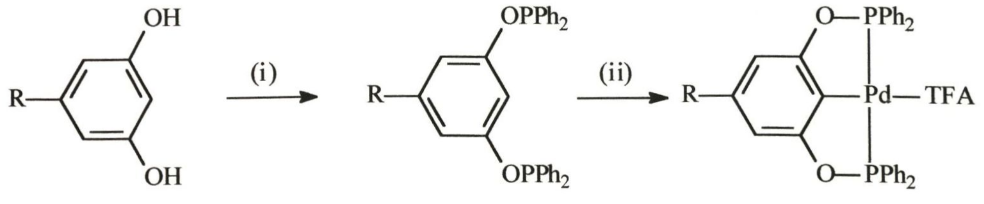


38

4.3 Results and Discussion

4.3.1 Synthesis of palladium bis(phosphinite) 'PCP'-pincer complexes 37a and 37b

The ligands resorcinolbis(diphenyl)phosphinite, **39a** and orcinolbis(diphenyl)phosphinite), **39b** are easily synthesised in good yields by the reaction of the appropriate aromatic diol with chlorodiphenylphosphine in toluene in the presence of triethylamine (scheme 4.2). The ease of synthesis of these ligands from inexpensive starting materials is one advantage of these compounds over the rather tedious preparation of 1,3-bis(phosphino)benzene ligand. Simply by reacting these ligands with palladium trifluoroacetate in THF at room temperature for just 2 hours gives the 'PCP'-pincer complexes $[\mathrm{Pd}\{\mathrm{OC(O)CF_3}\}\{\mathrm{C_6H_3\text{-}2,6\text{-}(OPPh_2)_2}\}]$ **37a** and $[\mathrm{Pd}\{\mathrm{OC(O)CF_3}\}\{\mathrm{C_6H_2\text{-}4\text{-}CH_3\text{-}2,6\text{-}(OPPh_2)_2}\}]$ **37b** in good yields (scheme 4.2). The purified compounds were isolated as colourless solids in 85 and 78% yields respectively, upon recrystallisation from dichloromethane/ethanol. The complexes show excellent air and moisture stability; for instance **37a** shows no sign of decomposition in aerobic solution in the presence of water after 10 days.



39a: R = H
39b: R = Me

37a R = H
37b R = Me

(i) 2 $\mathrm{ClPPh_2}$, 2.2 $\mathrm{Et_3N}$, toluene, reflux.

(ii) $\mathrm{Pd(TFA)_2}$, THF.

Scheme 4.2 Outlined synthesis of 'PCP' ligands and complexes

4.3.2 Analysis of X-ray crystallographic data for 37a.

The molecular structure of catalyst **37a** was determined through a single crystal X-ray diffraction study. The molecular structure is shown in Fig. 4.1 together with the labelling scheme. The structure consists of two $\mathrm{Pd\{OC(O)CF_3\}\{C_6H_3\text{-}2,6\text{-}(OPPh_2)_2\}}$ molecules in the asymmetric unit. The geometry of the palladium centre is distorted square planar and is grossly similar to that of the complex **36.**[11] The X-ray analysis confirms that palladation of the pincer ligand has occurred and that the two P-donor groups are in a distorted *trans* configuration. Selected bond lengths are listed in table 4.1.

Table 4.1 Selected bond lengths (Å) for **37a**

Bonds	**Bond lengths (Å)**
Pd(1)-C(1)	1.99(2)
Pd(1)-P(1)	2.28(6)
Pd(1)-P(2)	2.28(6)
Pd(1)-O(3)	2.09(18)
P(1)-O(2)	1.63(16)
P(2)-O(1)	1.60(16)
O(1)-C(2)	1.39(3)
O(2)-C(6)	1.38(3)
C(6)-C(1)	1.41(3)
C(1)-C(2)	1.40(3)
O(3)-C(7)	1.29(3)

The bond distance of 1.99(2) Å for the palladium atom and the metallated carbon atom for **37a** is the same as the distance between the palladium atom and the metallated carbon atom of the phenyl ring for complex $[\{\overline{\mathrm{Pd}(\mu\text{-}\mathrm{Cl})\{\mathrm{P(OC}}\mathrm{_6H_2\text{-}2,6\text{-}{}^{t}Bu_2)(OC_6H_3\text{-}2,4\text{-}{}^{t}Bu_2)_2}\}\}_2]$ **22**. While the palladium phosphorus distance of 2.28(6) Å for complex **37a** is longer than that of the palladium phosphorus distance for the metallated phosphite complex **22,** which is 2.16(7) Å. Similarly the phosphorus oxygen distance is slightly longer at 1.63(16) Å for P(1)-O(2) compared to 1.53(5) Å for the phosphorus oxygen bond distance for **22**.

The trifluoroacetate ligand coordinates in a unidentate, non-symmetrical fashion. This results in greater steric repulsion between the non-coordinated oxygen (O4) and the phenyl residues on the phosphorus atom labelled P1 than those on P2. This is reflected in the slightly longer bond distance of 1.63(16) Å for P(2)-O(1) in comparison to 1.603 Å for P(1)-O(2). Similarly this is reflected in the considerably larger angle between O(3)-Pd(1)-P(1) (104.8(5) °) than between O3-Pd1-P2 (94.5(5) °). Selected bond angles are listed in table 4.2.

Table 4.2 Selected bond angles (°) for **37a**.

Bonds	**Bond angles (°)**
O(3)-Pd(1)-P(1)	104.8(5)
O(3)-Pd(1)-P(2)	94.5(5)
C(1)-Pd(1)-P(1)	81.5(6)
C(1)-Pd(1)-P(2)	79.3(6)
P(1)-Pd(1)-P(2)	160.2(2)
C(1)-Pd(1)-O(3)	173.7(8)
Pd(1)-P(2)-O(1)	104.8(6)
O(1)-C(2)-C(1)	115.4(17)
C(2)-C(1)-Pd(1)	122.8(15)
C(1)-C(6)-O(2)	119.3(19)
O(2)-P(1)-Pd(1)	103.7(6)
C(2)-O(1)-P(2)	117.2(13)
Pd(1)-O(3)-C(7)	122.9(15)

The metallation of the phosphinite 'PCP' pincer ligand leads to the formation of a five membered chelate ring. This transformation of geometry implies new strains. On a plane, the angles of a regular pentagon are equal to 107° each. Considering that the members of the metallated ring are almost in the same plane the slight deformations allow a smooth flexibility. The theoretical model fits well with reality. Indeed the summation of the inside angles of the pentagon is equal to 539° (5 x 107° = 535°). However each individual angle is not equal to 107°, there are many variations. The C(2)-C(1)-Pd(1) angle is imposed by the phenyl ring geometry, thus the angle is 122.8° instead of 107°. However this is closely related to the value for the same angle in the metallated palladium complex **22** that has a value of 120.5°. As the geometry around the palladium centre is distorted square planar, the angles deviate significantly from 90°. The C(1)-Pd(1)-P(2) angle is 79.3° this is similar to the P-M-C bite angle of **22** which was found to be 81°. Finally the O(1)-C(2)-C(1) angle at 115.4° is reduced compared to an ideal sp^2 carbon, which is 120°.

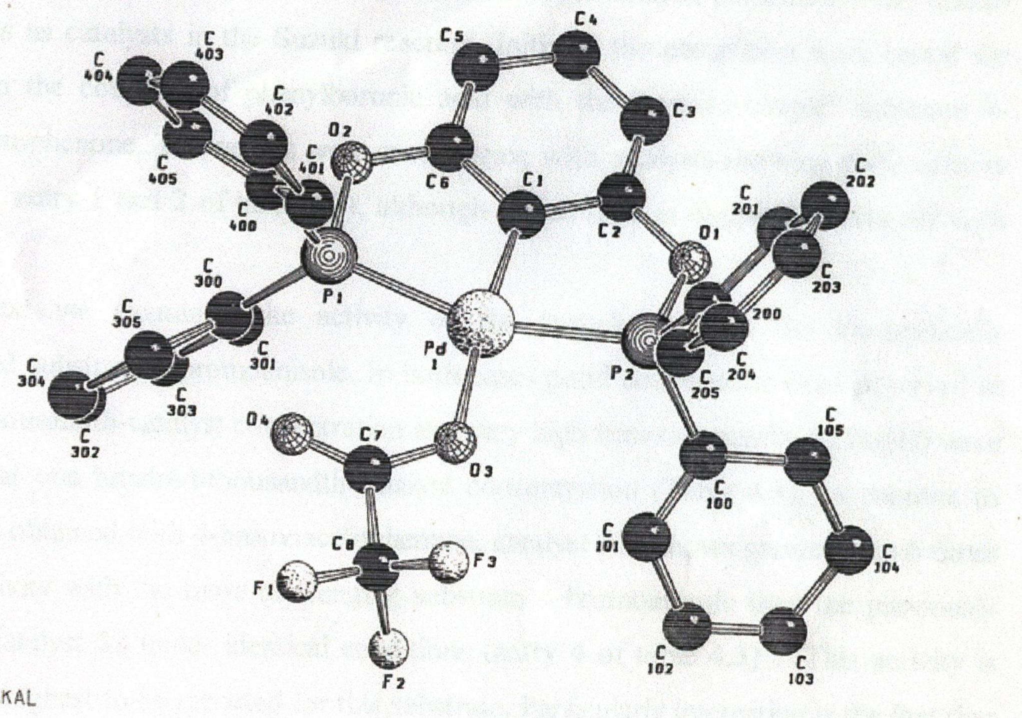


Fig 4.1 X-ray structure of $Pd\{OC(O)CF_3\}\{C_6H_3\text{-}2,6\text{-}(OPPh_2)_2\}$ (37a)

4.3.3 Reactivity of compound 37a in the Suzuki reaction

This work is among the first report on the application of palladium 'PCP'-pincer complexes as catalysts in the Suzuki reaction. Initially, the complexes were tested for activity in the coupling of phenylboronic acid with the 'easy-to-couple' substrate 4-bromoacetophenone. The results were encouraging with catalysts showing good activity at 130°C (entry 1 and 2 of table 4.3), although not as high as obtained previously with **22**.[3]

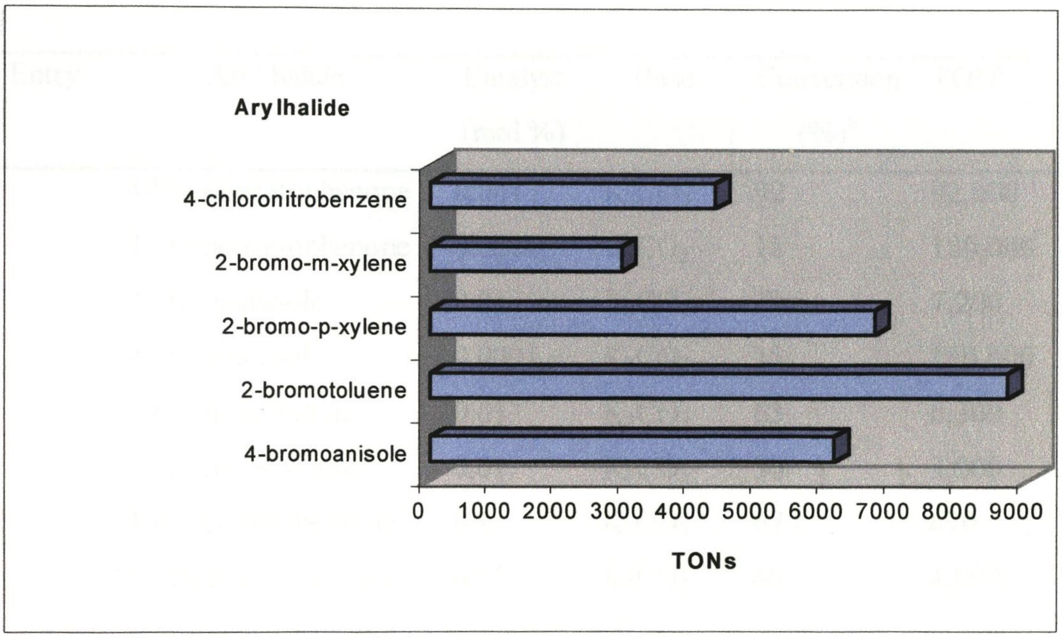
Next we examined the activity of the complexes with the electronically deactivated substrate 4-bromoanisole. In both cases good conversions were observed at one ten-thousandth-catalyst concentration and very high turnover numbers (TONs) were observed at one hundred-thousandth catalyst concentration (Table 4.3). In contrast to the results obtained with 4-bromoacetophenone, catalyst **37a** shows greater than 6 times higher activity with the more challenging substrate 4-bromoanisole than the previously reported catalyst **22** under identical conditions (entry 4 of table 4.3) .[3] This activity is one of the highest to be reported for this substrate. Particularly interesting is the fact that catalyst **37a** and **37b** couple 4-bromoanisole with nearly the same activity as they show in the coupling of 4-bromoacetophenone. This may imply that the oxidative addition of the aryl bromide is not the rate-limiting step in the catalytic cycle. The catalysts show moderate to good activity at low concentrations in the coupling of the sterically hindered, electronically deactivated substrates 2-bromotoluene, 2-bromo-*p*-xylene and even 2-bromo-*m*-xylene. By comparison, palladium complexes of the ligands **34** and PBu^t_3 show TONs in the range 82-94 [mol product.(mol Pd)$^{-1}$] for these substrates, albeit run at lower temperatures.[4b,6]

Table 4.3 Suzuki coupling of aryl halides with phenylboronic acid catalysed by palladium 'PCP'-pincer complex **37a**.

Entry	Aryl halide	Catalyst (mol %)	Base	Conversion (%)[b]	TON[c]
1	4-bromoacetophenone	0.001	K_2CO_3	59	59,000
2	4-bromoacetophenone	0.0001	K_2CO_3	19	190,000
3	4-bromoanisole	0.01	K_2CO_3	61	6,100
4	4-bromoanisole	0.0001	K_2CO_3	19	190,000
5	2-bromotoluene	0.01	K_2CO_3	87	8,700
6	2-bromo-*p*-xylene	0.01	K_2CO_3	67	6,700
7	2-bromo-*m*-xylene	0.01	K_2CO_3	29	2,900
8	4-chloronitrobenzene	0.01	K_2CO_3	41	4,300
9	4-chloronitrobenzene	0.01	K_3PO_4	25	2,500
10	4-chloronitrobenzene	0.01	$NaOBu^t$	0	0
11	4-chloronitrobenzene	0.01	KF	5	500
12	4-chloronitrobenzene	0.01	KF[d]	3	300

[a] Reaction conditions: 1.0 mmol aryl halide, 1.5 mmol $PhB(OH)_2$, 2.0 mmol base, 5 ml toluene, catalyst added in THF solution (0.1 ml), 130 °C, 18 h. [b] Determined by GC, based on aryl halide. [c] Defined as mol product per mol catalyst. [d] Solvent: 5 ml THF, 75 °C.

Graph 4.2 The plot of arylhalide versus TONs achieved with **37a** as catalyst.



The graph 4.2 is a 3-D representation of the reactivity of 0.01 mol% **37a** as catalyst in the Suzuki coupling of a wide range of substrates. It clearly shows the different rates of activity of **37a** with chemically different substrates. The best result was with the coupling of 2-bromotoluene with phenyl boronic acid

4.3.4 Reactivity of compound 37b in the Suzuki reaction.

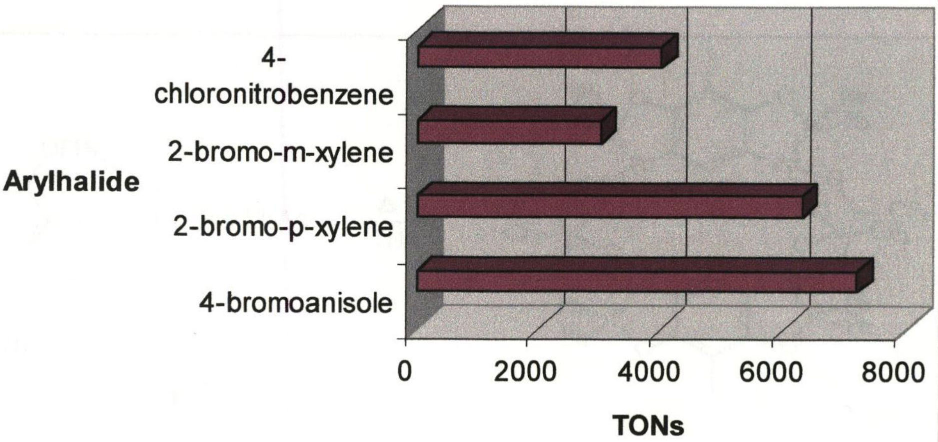
Whilst it is difficult to establish any clear trends in catalyst activity on these preliminary data, on average **37b** shows slightly higher activity than **37a** in reactions at 0.01 to 0.001 mol % catalyst concentration, possibly due to the fact that **37b** has the more electron-rich Pd centre. At 0.0001 mol % catalyst concentrations **37a** seems more effective; this may be due to slightly higher stability and thus longevity of the catalyst. However, the catalyst **37b** shows higher activity for the coupling of 4-chloronitrobenzene with phenylboronic acid (entry 8 of table 4.4) than the catalysts **37a** (entry 8 of table 4.3).

Table 4.4 Suzuki coupling of aryl halides with phenylboronic acid catalysed by palladium 'PCP'-pincer complex **37b**.

Entry	Aryl halide	Catalyst (mol %)	Base	Conversion (%)[b]	TON[c]
1	4-bromoacetophenone	0.001	K_2CO_3	92	92,000
2	4-bromoacetophenone	0.0001	K_2CO_3	18	180,000
3	4-bromoanisole	0.01	K_2CO_3	72	7,200
4	4-bromoanisole	0.0001	K_2CO_3	15	150,000
5	2-bromo-*p*-xylene	0.01	K_2CO_3	63	6,300
6	2-bromo-*m*-xylene	0.01	K_2CO_3	30	3,000
7	4-chloronitrobenzene	0.1	K_2CO_3	67	670
8	4-chloronitrobenzene	0.01	K_2CO_3	40	4,000

[a] Reaction conditions: 1.0 mmol aryl halide, 1.5 mmol $PhB(OH)_2$, 2.0 mmol base, 5 ml toluene, catalyst added in THF solution (0.1 ml), 130 °C, 18 h. [b] Determined by GC, based on aryl halide. [c] Defined as mol product per mol catalyst.

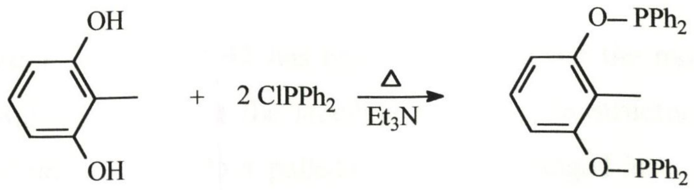
Graph 4.3 The plot of aryhalide versus TONs achieved with **37b** as catalyst.



The graph 4.3 is a 3-D representation of the reactivity of 0.01 mol% **37b** as catalyst in the Suzuki coupling of a wide range of substrates. It clearly shows the different rates of activity of **37b** with chemically different substrates. The best result was with the coupling of 4-bromoanisole with phenyl boronic acid.

4.3.5 Synthesis of the ligand 2-methylresorcinolbis(diphenyl)phosphinite (40)

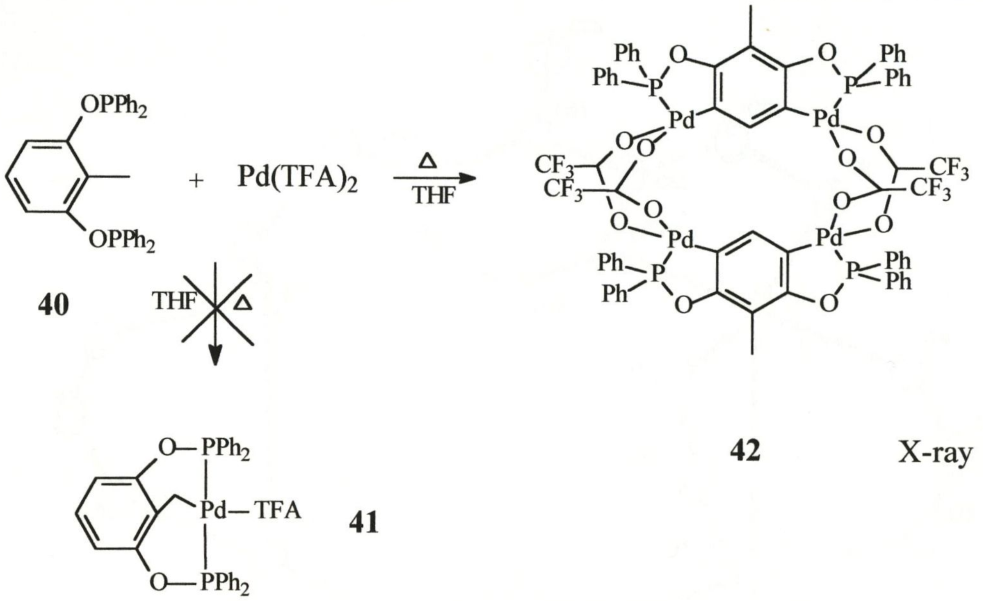
The ligand 2-methylresorcinol(diphenyl)phosphinite **40** is easily synthesised in high yield by refluxing in toluene, 2-methylresorcinol with two equivalents of chlorodiphenylphosphine in the presence of triethylamine (scheme 4.3).



40

Scheme 4.3 Synthesis of ligand **40**

However, when the ligand **40** is reacted with palladium trifluoroacetate in THF at reflux failed to give the expected product **41** but formed instead the tetra metallated palladium complex **42** (scheme 4.4)



Scheme 4.4 Synthesis of the metallated complex **42**

The fact that complex **42** is formed rather than complex **41** maybe attributed to the steric factor involved if complex **41** was formed. Therefore the formation of complex **42** is formed in such a way that steric repulsion is at a minimum.

4.3.6 Analysis of X-ray crystallographic data for 42

The crystal structure of **42** has been determined and the molecular structure is shown in Fig 4.2 together with the labelling scheme. The structure consists of eight molecules in the unit cell with four palladacycle units arranged in a cyclic tetramer with an approximate C_2 symmetry. This is the first example of a tetranuclear palladium phosphosphinite complex. However, similar tetrameric palladium complexes have been synthesised and their structure confirmed by X-ray diffraction.[15]

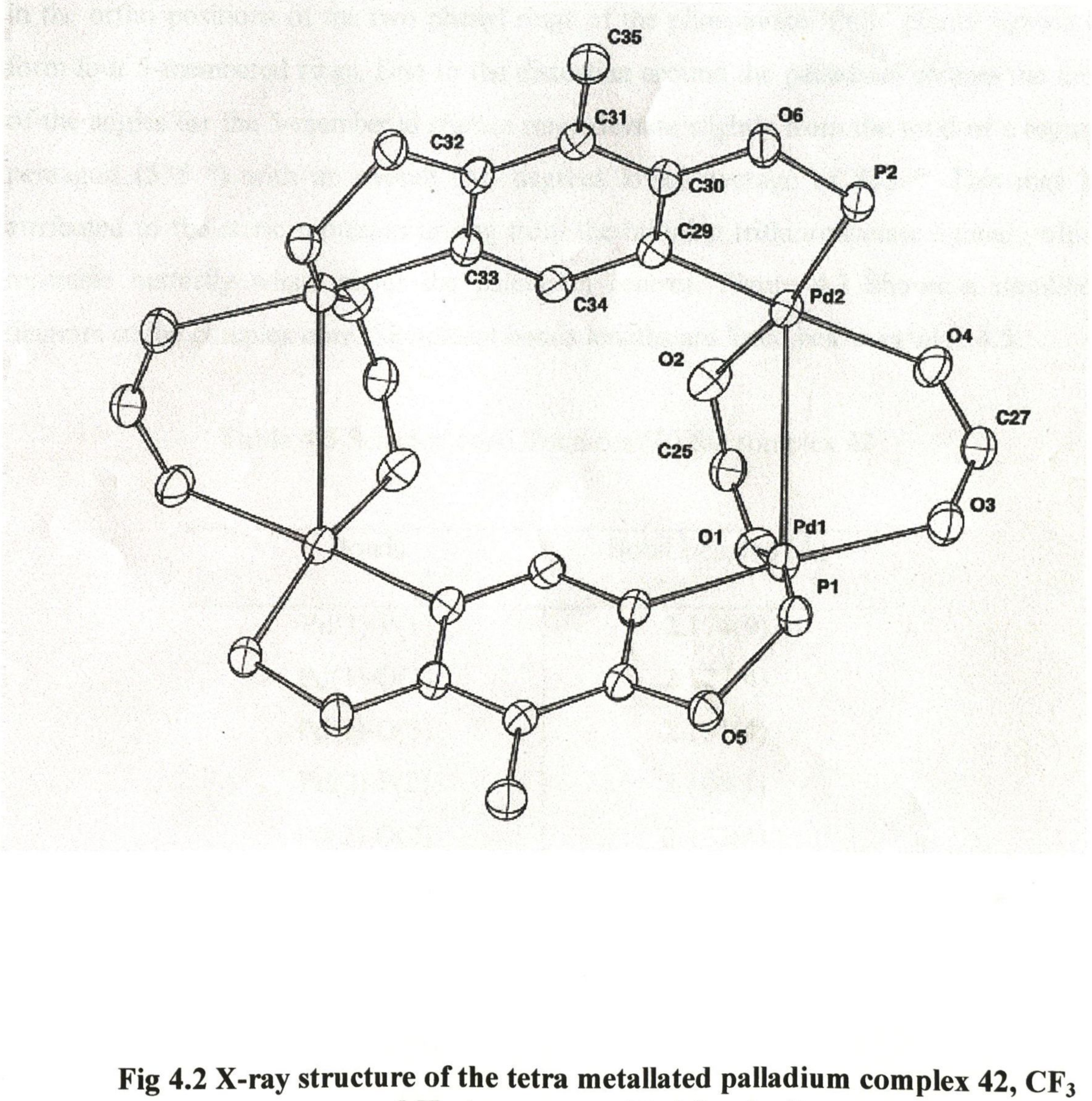


Fig 4.2 X-ray structure of the tetra metallated palladium complex 42, CF_3 and H atoms are omitted for clarity.

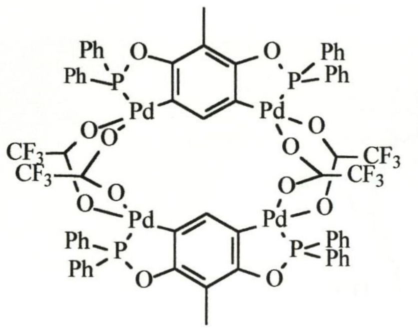
Examples of two such complexes are the tetranuclear pyridine functionalised N-heterocyclic carbene complex $[Pd(C\text{-}N)Me(O_2CCF_3)]_4$, (C-N = 3-mes-1-(2-picolyl)-imidazolin-2-ylidene) **43** which was reported by Hursthouse *et al.*[16] and the tetrameric oxapalladacycle $[Pd(2\text{-}C_6H_4CO_2)(PPh_3)]_4$ **44** which was reported by Echavarren *et al.* .[17] The geometry around the palladium is distorted square planar. Metallation has occurred in the ortho positions of the two phenyl rings of the phosphinite 'PCP' pincer ligands to form four 5-membered rings. Due to the distorting around the palladium centres the total of the angles for the 5-membered chelate rings deviate slightly from the total of a regular pentagon (535 °) with an overall two degrees lower average of 533 °. This may be attributed to the steric repulsion arising from the bridging trifluoroacetate ligands, which resemble butterfly wings about the palladium centres. Figure 4.3 shows a simplified diagram of the complex core. Significant bonds lengths are listed below in table 4.5.

Table 4.5 Selected bond distances (Å) for complex **42**

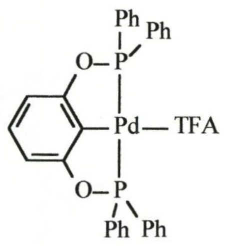
Bonds	Bond Lengths (Å)
Pd(1)-P(1)	2.174(9)
Pd(1)-O(1)	2.127(4)
Pd(1)-O(3)	2.151(4)
Pd(2)-P(2)	2.168(1)
Pd(2)-O(2)	2.142(4)
Pd(2)-O(4)	2.157(3)
P(1)-O(5)	1.631(3)
P(2)-O(6)	1.622(3)
Pd(2)-C(29)	2.001(5)
Pd(1)-C(33^{i})	2.007(8)

An examination of the measured bond lengths within the structure of **42** is worthy of note. The bond distance between the metallated carbon atoms and the palladium atoms is 2 Å. There is a slight difference between the P-O bond lengths of the phosphinite ligands with P(1)-O(5), 1.631 Å and P(2)-O(6), 1.622 Å. The bond lengths between the palladium atoms and the oxygen atoms of the trifluoroacetate ligands range form 2.127 –

2.157 Å that is an overall difference of 0.03 Å. This is most likely due to the strain imposed the minimising of steric repulsion between the two bridging ligands.



42



37a

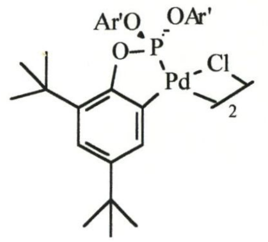


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Table 4.6 Comparison between relevant bond lengths of the metallated complexes **42**, **37a** and **22**.

Bond (Å)	**42**	**37a**	**22**
Pd-P	2.172[a]	2.284[a]	2.167
Pd-O	2.144	2.093	-
Pd-C	2.004[a]	1.99	1.999
P-O	1.626[a]	1.621[a]	1.587[a]
P-C	1.787	1.817[a]	-
C-O	1.278[a]	1.327	1.411
C-F	1.373[a]	1.305[a]	-
C-C	1.39[a]	1.386[a]	1.488[a]

a = average value

As can be seen from table 4.6 the main differences in bond lengths is that of Pd-P which has an overall difference of 0.117 Å

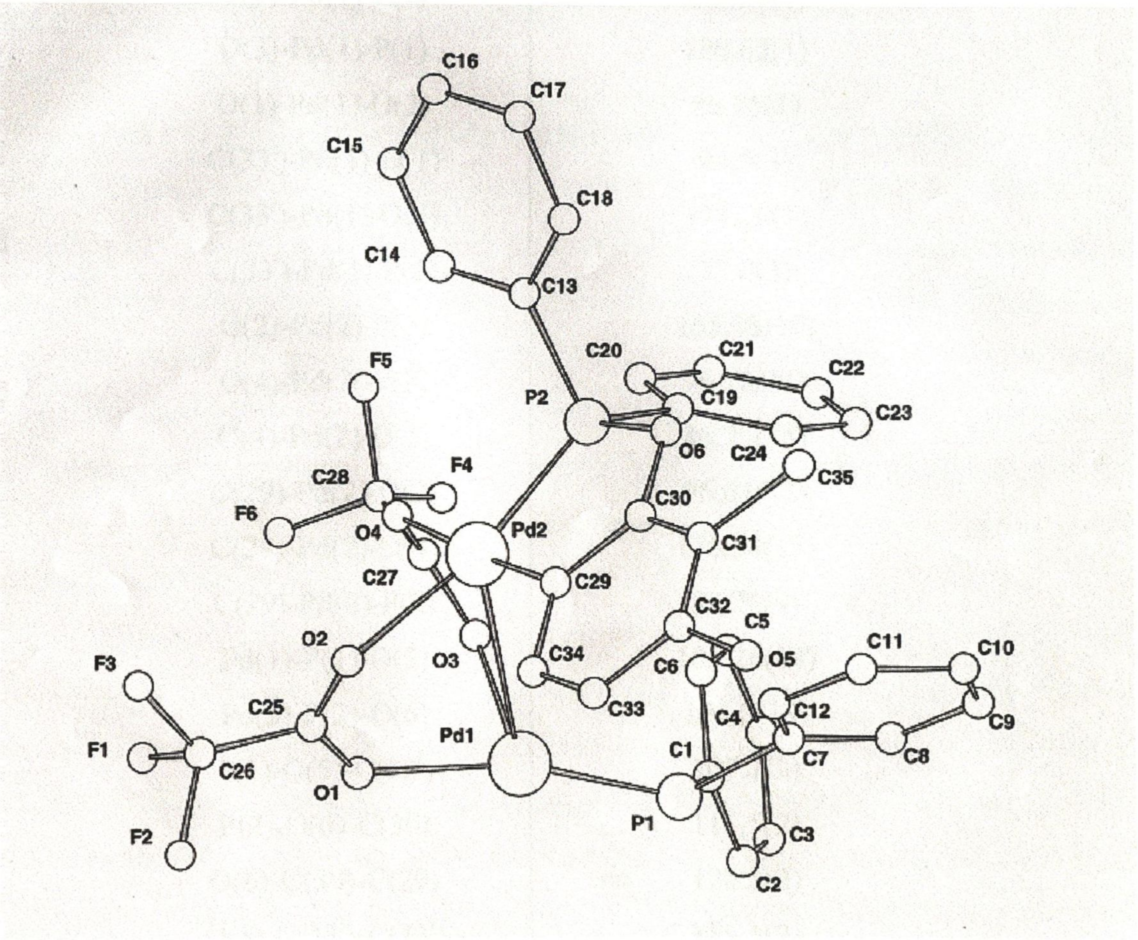

Fig 4.3 X-ray structure of the tetra metallated palladium complex (42) from a different view

Table 4.6 Selected bond angles (°) for complex **42**

Bond	Bond angles (°)
O(1)-Pd(1)-P(1)	165.28(1)
O(3)-Pd(1)-P(1)	100.62(1)
O(1)-Pd(1)-O(3)	86.75(1)
C(33^{i})-Pd(1)-O(1)	94.9(3)
C(33^{i})-Pd(1)-O(3)	175.78(1)
C(33^{i})-Pd(1)-P(1)	77.0(3)
O(2)-Pd(2)-P(2)	165.98(10)
O(4)-Pd(2(-P(2)	96.28(11)
O(4)-Pd(2)-O(2)	86.75(15)
C(29)-Pd(2)-O(2)	96.63(12)
C(29)-Pd(2)-O(4)	176.54(13)
C(29)-Pd(2)-P(2)	80.26(9)
Pd(1)-P(1)-O(5)	105.26(14)
Pd(2)-P(2)-O(6)	108.9(13)
P(1)-O(5)-C(32^{i})	107.7(2)
P(2)-O(6)-C(30)	111.5(2)
O(6)-C(30)-C(29)	120.8(2)
O(5)-C(32^{i})-C(33^{i})	119.1(2)
Pd(1)-C(33^{i})-C(32^{i})	117.53(15)
Pd(2)-C(29)-C(30)	118.46(15)

The C(30)-C(29)-Pd(2) and C(32^{i})-C(33^{i})-Pd(1) angles are imposed by the phenyl ring geometry, thus the angles are 118.4 and 117.5 ° respectively instead of 107 °. As the geometry around the palladium centre is distorted square planar the angles deviate significantly from 90 ° as can be seen by the P-M-C bite angles which are 80.2 ° and 77.0 °. However these bite angles compare well with the bite angles for complex **37a** which has a value of 79.3 ° and the bite angle for the complex **22** which has a value of 81 °.

Finally the O(6)-C(30)-C(29) angle at 117.5 ° and the O(5)-$C(32^{i})$-$C(33^{i})$ angle at 119.2 ° are reduced compared to the ideal sp^2 carbon, which is 120 c. However both compare well to the O(1)-C(2)-C(1) angle for complex **37a** which has an angle of 115.4 °.

4.3.7 A study of the reaction conditions

The 'PCP'-pincer complexes $Pd\{OC(O)CF_3\}\{C_6H_3\text{-}2,6\text{-}(OPPh_2)_2\}$ **37a** and $Pd\{OC(O)CF_3\}\{C_6H_2\text{-}4\text{-}CH_3\text{-}2,6\text{-}(OPPh_2)_2\}$ **37b** show moderate activity in the coupling of activated aryl chlorides (Table 4.3 and table 4.4); however, little or no activity was observed with deactivated chlorides. Comparing entries 8 to 12 it can be seen that the nature of the base plays a major role in the efficiency of coupling of the chlorides. Particularly interesting was the fact that KF proved to be a very poor choice of base, even when toluene was replaced with THF. This is in direct contrast with the finding by Buchwald *et. al.* that this base-solvent mixture can give high activity with palladium phosphine systems.[6]

Milstein *et. al.* stated that the metallated complexes **35a** and **35b** were not able to operate in the usual Pd(0)/Pd(II) cycle in the Heck coupling reaction.[10] This is due to very high persistence of the dual chelate, as it was shown that the complexes were recovered unchanged except for the exchange of the labile ligand TFA for halogen after the completion of reactions which are carried out for several days at 140 ° - 160 °C.[18] Therefore the reaction pathway maybe Pd(II)/Pd(IV) however a Pd(0)/Pd(II) pathway at this stage can not be totally ruled out. The dechelation of the first phosphine arm is not so improbable, as the 'PCP' complexes **35a** and **35b** actually possess an essentially distorted configuration, quite far from square planar. As according to X-ray data of complex **35b** the angle P-Pd-P is as small as 152 °, which shows large strain.[18] The strain can be relieved by the dechelation. Thus it can be noted that the 'PCP' complexes may be activated at elevated temperature, which would encourage disassembly of the bis-palladacycle structure.[18]

4.4 Conclusion

The formation of the 'PCP'- pincer ligands resorcinolbis(diphenyl)phosphinite, **39a**, orcinolbis(diphenyl)phosphinite), **39b** and 2-methylresorcinol(diphenyl)phosphinite **40** by reaction of the appropriate diol with chlorodiphenylphosphine at reflux temperature has been shown. The starting materials are commercially available and are cheap. The subsequent reaction of the ligands **39a** and **39b** with palladium trifluoroacetate resulted in the formation of the two 'PCP'-pincer complexes **37a** and **37b** in reasonably good yield. While the reaction of the ligand **40** with palladium trifluoroacetate led to the formation of the tetrameric palladium complex **42** instead of the predicted palladium 'PCP'-pincer complex **41**. The complexes **37a** and **37b** were employed as catalysts for the coupling of various aryl halides with phenylboronic acid in the Suzuki coupling reaction. These bis(phosphinite) 'PCP' -pincer complexes have proven ideal catalysts for the coupling of deactivated and sterically hindered aryl bromides as they are inexpensive and very easily synthesised. Complex **37a** shows high catalytic activity for the coupling of the deactivated aryl halide, 4-bromoanisole with turnover numbers of up to 190, 000 [mol product.(mol Pd)$^{-1}$]. While complex **37b** showed a somewhat lower activity for the same substrate with TONs of up to 150,000 achieved. However **37b** showed good activity with the sterically hindered substrate 2-bromo-*p*-toluene with TONs of up to 6,300 achieved.

Future work should involve a more in-depth look at the pathway involved in the Suzuki coupling reaction when 'PCP'-pincer complexes are used as catalysts. Similarly to explore the activity of the tetrameric palladium complex **42** in Suzuki coupling reactions. Another aspect of this work could be to synthesis 'PCP'-pincer phosphite ligands and their corresponding palladium complexes with the aspect as potential carbon-carbon bond formation catalysts.

4.5 Experimental

4.5.1 General Experimental

All chemicals were commercially available. The chlorodiphenylphosphine was freshly distilled and each of the diols were azotropically dried using toluene prior to use. The Pd(TFA)$_2$ was prepared according to the literature procedure.[19] In all cases, the solvents were freshly distilled under nitrogen from sodium/benzophenone ketyl. All the reactions were carried out in a dry nitrogen atmosphere. The catalytic reactions were carried out using Radelys multi reaction carousal. ^{1}H NMR spectra were recorded on a WM-400 Bruker (at 400 MHz) instrument. Gas chromatography analyses were performed on a Varian 3300 gas chromatograph, with FID, a 20-metre capillary column and a 4290 integrator.

4.5.2 Synthesis of the ligand Resorcinolbis(diphenyl)phosphinite (39a)

To a solution of resorcinol (2.5 g, 23.0 mmol) and chlorodiphenylphosphine (8.4 ml, 46.0 mmol) in toluene (40 ml) was added triethylamine (7.0 ml, 50.0 mmol) dropwise. The resultant mixture was then heated at reflux for 18 hours. After cooling, the volatiles were removed *in vacuo*, the residue was extracted with THF (20 ml) and the resultant solution was filtered through celite. The celite was washed with THF (2 x 20 ml), the extracts were combined and the solvent was removed in *vacuo* to yield the title product as an air sensitive yellow-orange solid that was not purified further (8.2 g, 75%).

^{1}H NMR (400 MHz, CDCl$_3$. 293 K) δ 6.84 (d, 2H, $^2J_{HH}$ = 8.0 Hz, 6,4-Hs of resorcinol ring); 7.02 (s, 1H, 1-H of resorcinol ring); 7.14 (t, $^3J_{HH}$ = 8.0 Hz,4-H of resorcinol ring); 7.44 (m, 12H, PPh$_2$); 7.63 (m, 8H, PPh$_2$) ppm.

^{31}P (161.9 MHz, CDCl$_3$, 293 K) δ 114.0 ppm

4.5.3 Synthesis of the ligand Orcinolbis(diphenyl)phosphinite (39b)

To a solution of 3,5-dihydroxytoluene (orcinol; 2.18 g, 17.6 mmol) and chlorodiphenylphosphine (7.2 ml, 39.4 mmol) in toluene (40 ml) was added triethylamine (7.0 ml, 50.0 mmol) dropwise. The resultant mixture was then heated at reflux for 18 hours. After cooling, the volatiles were removed *in vacuo*, the residue was extracted with THF (20 ml) and the resultant solution was filtered through celite. The celite was washed with THF (2 x 20 ml), the extracts were combined and the solvent was removed in *vacuo* to yield the title product as an air sensitive yellow-orange solid that was not purified further (8.5 g, 98%).

^{1}H NMR (400 MHz, $CDCl_3$. 293 K) δ 2.29 (s, 3H, CH3); 6.71 (s, 2H, 4,6-Hs of orcinol ring); 6.84 (s, 1H, 2-H of orcinol ring); 7.41 (m, 12H, PPh_2); 7.60 (m, 8H, PPh_2) ppm.

^{31}P (161.9 MHz, $CDCl_3$, 293 K) δ 111.3 ppm

4.5.4 Synthesis of Palladium bis(phosphinite) complex (37a)

A solution of palladium trifluoroacetate (0.100 g, 0.302 mmol) and ligand **39a** (0.144 g, 0.302 mmol) in THF (5.0 ml) was stirred under nitrogen at room temperature for 2 hours. The solvent was then removed *in vacuo*. The residue was washed with ethanol and then recrystallised from dichloromethane/ethanol as a colourless solid (0.175 g, 85%). Crystals suitable for crystal X-ray analysis were obtained by layering a solution of **37a** in dichloromethane with hexane.

^{1}H NMR (400 MHz, $CDCl_3$. 293 K) δ 6.74 (d, 2H, $^2J_{HH}$ = 8.0 Hz, 3,5-Hs of resorcinol ring); 7.12 (t, $^3J_{HH}$ = 8.0 Hz, 5-H of resorcinol ring); 7.57 (m, 12H, PPh_2); 7.90 (m, 8H, PPh_2) ppm.

^{31}P (161.9 MHz, $CDCl_3$, 293 K) δ 146.2 ppm.

^{19}F NMR δ - 74 (TFA) ppm.

Microanalysis: Calculated for $C_{32}H_{23}F_3O_4P_2Pd$: C 55.15; H 3.3 %. Found: C 54.85; H 3.55 %.

X-ray crystallographic data: (tabulated results describing data collection and refinement parameters are presented in appendix A).

A single crystal (0.50 x 0.50 x 0.20 mm) from layering dichloromethane and hexane was mounted on a glass fibre. Dr. S. M. Draper, Trinity College Dublin, solved the structure. $C_{32}H_{23}F_3O_4P_2Pd$, $M = 696.84$, orthorhombic, space group $P2_12_12_1$, Z = 4, a = 10.469(2), b = 15.8692(9), c = 17.2811(14) Å, $U = 2871.0(6)$ Å^3, $T = 293(2)$ K, μ(Mo-Kα) = 0.815 mm^{-1}, 2729 independent reflections measured, the final *R* factor was 0.0863 for 2189 reflections with $I > 2\sigma(I)$.

4.5.5 Synthesis of Palladium bis(phosphinite) complex (37b)

A solution of palladium trifluoroacetate (0.100 g, 0.302 mmol) and ligand **39b** (0.149 g, 0.302 mmol) in THF (5.0 ml) was stirred under nitrogen at room temperature for 2 hours. The solvent was then removed *in vacuo*. The residue was washed with ethanol and then recrystallised from dichloromethane/ethanol as a colourless solid (0.166 g, 78 %).

^{1}H NMR (400 MHz, $CDCl_3$. 293 K) δ 2.28 (s, 3H, CH3); 6.57 (s, 2H, 4,6-Hs of orcinol ring); 7.49 (m, 12H, PPh_2); 7.86 (m, 8H, PPh_2) ppm.

^{31}P (161.9 MHz, $CDCl_3$, 293 K) δ 145.6 ppm

Microanalysis: Calculated for $C_{33}H_{25}F_3O_4P_2Pd$: C 55.75; H 3.5 %. Found: C 55.10; H 3.30 %.

4.5.6 Synthesis of the ligand 2-methylresorcinolbis(diphenyl)phosphinite (40)

To a solution of 2-methylresorcinol (2.5 g, 20.1 mmol) and chlorodiphenylphosphine (7.3 ml, 40.3 mmol) in toluene (40 ml) was added triethylamine (7.0 ml, 50.0 mmol) dropwise. The resultant mixture was then heated at reflux for 18 hours. After cooling, the volatiles were removed in *vacuo*, the residue was extracted with THF (20 ml) and the resultant solution was filtered through celite. The celite was washed with THF (2 x 20 ml), the extracts were combined and the solvent was removed in *vacuo* to yield the title product as an air sensitive pale yellow solid that was not purified further (8.9 g, 90%).

^{1}H NMR (400 MHz, $CDCl_3$. 293 K) δ 2.78 (s, 3H, CH_3); 6.85 (d, 2H, $^2J_{HH}$ = 8.0 Hz, 3,5-Hs of resorcinol ring); 6.97 (t, $^3J_{HH}$ = 8.0 Hz,4-H of resorcinol ring); 7.38 (m, 12H, PPh_2); 7.62 (m, 8H, PPh_2) ppm.

^{31}P (161.9 MHz, $CDCl_3$, 293 K) δ 111.7 ppm

4.5.7 Synthesis of the $[Pd_2(\mu\text{-}O_2CCF_3)_2\{MeC_6H_1\text{-}2,6\text{-}(OPPh_2)_2\}]_2$ (42)

A solution of palladium trifluoroacetate (0.100 g, 0.302 mmol) and ligand **40** (0.149 g, 0.302 mmol) in THF (5.0 ml) was stirred under nitrogen at room temperature for 2 hours. The solvent was then removed in *vacuo*. The residue was washed with ethanol and then recrystallised from dichloromethane/ethanol as a red solid (0.250 g, 89%). Crystals suitable for crystal X-ray analysis were obtained by layering a solution of **42** in dichloromethane with hexane.

^{1}H NMR (400 MHz, $CDCl_3$. 293 K) δ 2.18 (s, 6H, CH_3); 6.41 (s, 2H, 4-H of resorcinol ring); 6.97(mm, 40H PPh_2) ppm.

^{31}P (161.9 MHz, $CDCl_3$, 293 K) δ 161.2 ppm

4.6 References

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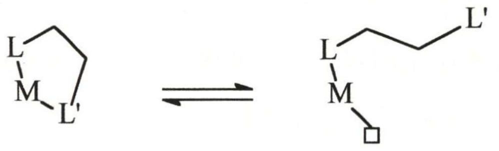
Chapter 5

Design and Synthesis of New Ligand Sets and Their Related Palladium Complexes

5.1 Introduction

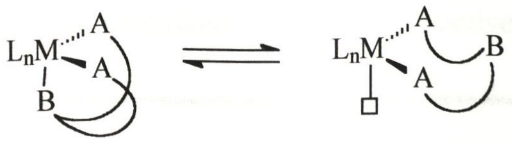
The presence of an active site or the ability to generate an active site in a primary dissociation step in a metal complex is vital for catalysis. An active site can equate to a vacant coordination site. It can also be used to stabilise ligands that exist only transiently as 'free' molecules (*e.g.* alkylidynes). The main characteristic of an active site is that it can bind extra ligands. Another desirable feature of a transition metal complex in catalysis is its ability to vary its oxidation state.



□ = vacant coordination site

Scheme 5.1.1 Formation of an active site via a hemi-labile process masking

One method for the opening of an active site is the dissociation of a bulky ligand from a complex. However, in order for this to occur the residual ligands must also be relatively sterically encumbered, thus the size of the incoming species is limited. An alternative method is to "mask" the active site with a hemi-labile chelate ligand, that is a ligand in which one donor readily dissociates from the metal centre (scheme 5.1.1). A second method for the "unmasking" of an active site is the reductive elimination of two fragments from the coordination sphere (scheme 5.1.2). The resultant complex is not only coordinatively unsaturated, but also reduced and consequently able to undergo facile oxidative addition reactions.



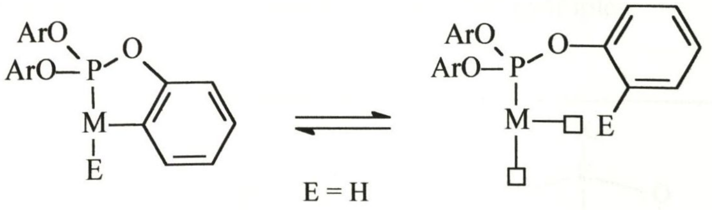
□= vacant coordination site

Scheme 5.1.2 Formation of an active site masking via a reductive elimination process

The previous Chapters (Chapters 2, 3 and 4) have exploited the use of triarylphosphite and 'PCP'-pincer phosphinite ligands as masks of active sites in late transition metal (LTM) complexes. This maybe achieved in two distinct ways, which are as follows:

5.1.1 Orthometallation

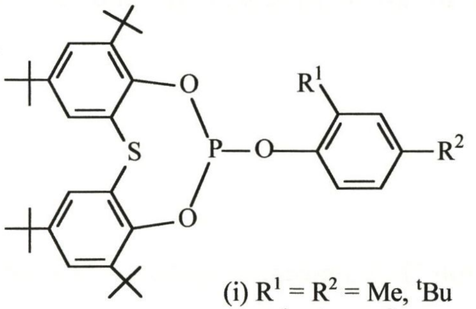
The first examples of active site masking exploited is the orthometallation reactions of bulky tris(2,4-di-*tert*-butylphenyl)phosphite and 'PCP' pincer complexes for active site masking (*c.f.* chapters 2, 3 and 4).[1] The reverse process, de-orthometallation (scheme 5.1.3), effectively "unmasks" the active sites.[2,3] The resultant metallated LTM complexes, $[IrH\{P(OC_6H_2\text{-}2,4\text{-}{}^tBu_2)_2(OC_6H_3\text{-}2,4\text{-}{}^tBu_2)\}(cod)]$ and $[\{Pd(\mu\text{-}Cl)\{P(OC_6H_2\text{-}2,6\text{-}{}^tBu_2)(OC_6H_3\text{-}2,4\text{-}{}^tBu_2)_2\}\}_2]$ have been used as catalysts in imine hydrogenation[3] and the Heck arylation of olefins respectively.[1] This latter example is particularly notable for two reasons. Firstly, the catalysis is very efficient, with an order of magnitude higher turnover number (TON) observed than for the previously reported by Herrmann and co-workers[4] and up two orders of magnitude greater TON than the standard Pd(acetate)$_2$/tris-*o*-tolylphosphine system. Secondly, the ligand is extremely cheap (~150th the cost of tri-*o*-tolylphosphine) and can easily be modified.



Scheme 5.1.3 De-orthometallation of an arylphosphite generates an unmasked complex with 2 active sites.

5.1.2 Hemi-labile

The second approach to active site masking is the use of triarylphosphites with secondary donor groups (such as sulphur containing ligands) capable of coordinating in a hemi-labile fashion such as **43**. This chapter deals with the synthesis of such ligands and with the formation of their palladium complexes to yield potential catalysis for various catalytic processes such as carbon-carbon bond formation reactions (i.e. Heck & Suzuki coupling reactions) and also for olefin polymerisation reactions.

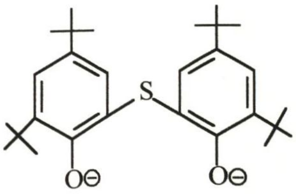


(i) $R^1 = R^2 = Me, {}^tBu$
(ii) $R^1 = {}^tBu, R^2 = Me$

43

5.1.3 The Ligands

The parent diols of the phenoxides **44** are extensively used in industry as antioxidants in polymers. Therefore, it is surprising that the coordination chemistry of the phenoxides has been limited to a few Ti, Zr[5] and Ni[6] examples.



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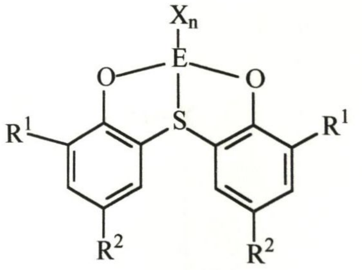


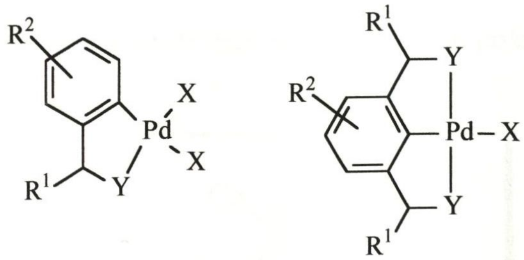
45a E = Si, n = 2, X = R, OR
45b E = P, n = 3, X = OR

The Ni complexes have found use as polypropylene photo-oxidation inhibitors, whilst the Ti and Zr complexes were studied for potential olefin polymerisation activity. Despite the paucity of its transition metal chemistry, **44** has been used extensively as a substituent in high coordinate phosphorus and silicon chemistry to give the compounds **45**.[7] The extent of the phosphorus-sulphur (P----S) interaction in **45b** was found to be strongly dependent on the size of the aromatic ring substituents, R. When $R^1 = R^2 = Me$, the P adopts a triganol bipyramidal structure with no P----S interaction. However, when $R^1 = R^2 = {}^tBu$ a P---S interactions results, giving a six coordinate phosphorus atom.[8] Consequently there is a possibility to see the hemi-labile nature of the ligands vary with steric profile, allowing to 'fine tune' the reactivity of the metal complexes that will be generated.

5.1.4 Catalysis

5.1.4.1 Heck and Suzuki coupling reactions, C-C bond formation reactions

In the last decade much attention has been paid to the Heck coupling of haloalkenes or haloarenes with alkenes and to the Suzuki coupling of haloalkenes or haloarenes with boronic acid derivatives. Much of this attention has been focussed on palladacycles. The vast majority of palladacycles posses anionic four-electron (bidentate) or six-electron (tridentate) donor ligands, with five-membered nitrogen-containing rings being the most common (scheme 5.1).[9]



$Y = NR_2, NR, PR_2, SR$
R^1, R^2 = alkyl, aryl
X = Cl, Br, I, OTf, OAc

Scheme 5.1 Examples of palladacycles

As has been describe in Chapter 1 the synthesis of palladacycles is facile and it is easy to tune their steric and electronic profile by simply changing the following:

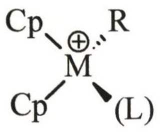
(i) the size of the metalacyclic ring (3-10 membered)
(ii) the nature of the metallated carbon atom (aliphatic, aromatic, etc.)
(iii) the type of donor atom (N-, P-, S-, O-, containing group) and its substituents (alkyl, aryl, etc.)
(iv) the nature of the X ligands (halide, triflate, or solvent, *e.g.* THF, H_2O).

These factors determine the form of the palladacycle whether the complex is dimeric, monomeric, neutral, or cationic.[10]

While high turnover numbers (TONs) were achieved with the palladated complexes $[\{Pd(\mu\text{-}Cl)\{P(OC_6H_2\text{-}2,6\text{-}{}^tBu_2)(OC_6H_3\text{-}2,4\text{-}{}^tBu_2)_2\}\}_2]$ **22**, $[Pd\{OC(O)CF_3\}\{C_6H_3\text{-}2,6\text{-}(OPPh_2)_2\}]$ **37a** and $[Pd\{OC(O)CF_3\}\{C_6H_2\text{-}4\text{-}CH_3\text{-}2,6\text{-}(OPPh_2)_2\}]$ **37b** it is a desirable goal to design and synthesis palladacycles based on different ligand backbones.

5.1.4.2 Olefin polymerisation

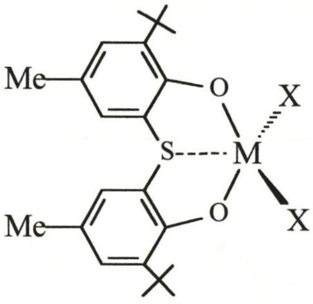
The use of early transition metal (ETM) metallocene based catalysts activated with methylaluminoxane (MAO) in the polymerisation of α-olefins has attracted considerable attention.[11] This is due to their ability to produce narrow molecular weight distribution polymers with controllable stereoregularity. The high activity of the cationic metallocene alkyl intermediates, 7, is attributed to the very electrophilic nature of the d^0-M^+ centre and the inherently high reactivity of the polarised M-C(alkyl) bond.



M = Ti, Zr, Hf

47

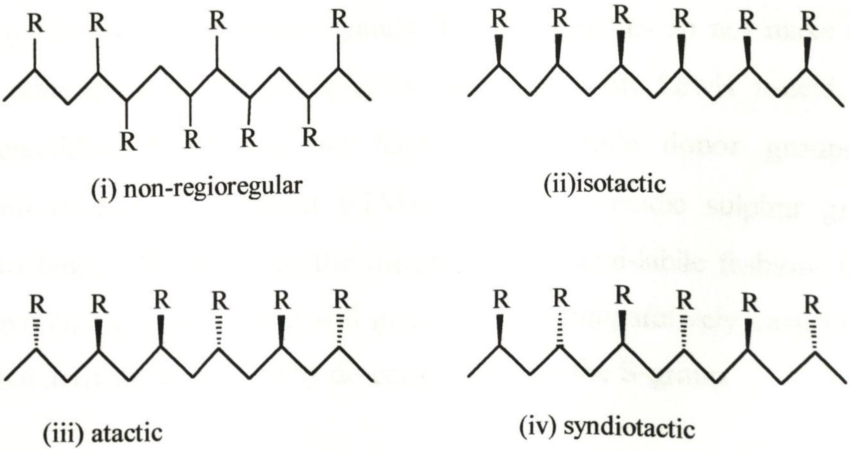
Recently, attention has turned to the use of alternative ligand systems such as amido (RR'N$^-$)^{12}, alkoxo (RO$^-$)^{13} and related polydentate ligands.^{14} Such ligands have the potential for simple steric and electronic 'tuning' and consequently for subtle modification of the catalytic activity. To this end complexes of thiobis(phenoxides) **44** of the type **47** have been synthesised and their catalytic abilities tested.^{6c}



M = Ti, Zr
X = Cl, R, OR

47

The rate of polymerisation was found to be an order of magnitude higher than with related ligands without the S-bridge and the polymer produced had a narrower polydispersivity. Both of these findings point to a significant role being played by the S-donor. Whilst regioregularity of the polymers formed with **47** as catalyst was high, stereoregularity was not. The stereoisomers of α-polyolefins is shown in fig 5.1.



(i) non-regioregular

(ii)isotactic

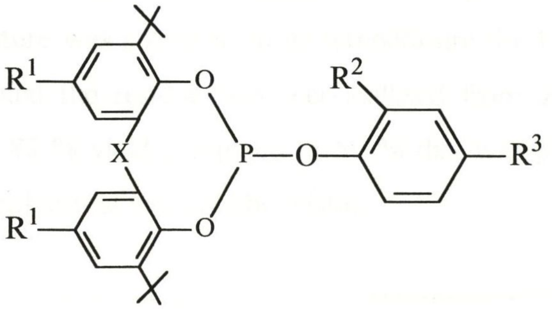
(iii) atactic

(iv) syndiotactic

Fig 5.1 Polymer sterochemistry

5.2 Aims of Research

In view of this ongoing success in the area of active site masking by triarylphosphite ligands it is hoped to extend this work to the second method of active site masking; Hemi-labile ligands of the type **43**. In this chapter the synthesis and characterisation of the ligands sets **43** and **48** are described. The ligands contain a donor group, which could potentially act as a hemi labile donor and therefore mask an active site.



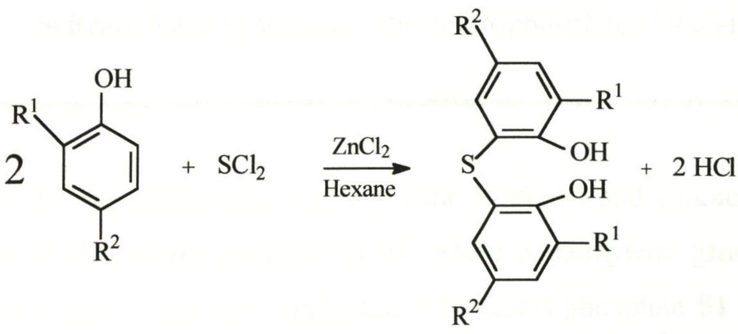
43 X = S, R^1 = ^{t}Bu, R^2 = R^3 = Me, ^{t}Bu
48 X = CH$_2$, R^1 = ^{t}Bu, R^2 = R^3 = Me, ^{t}Bu

As active site masking in late transition metal catalysis is another aspect of catalysis that has gained recent interest, it is desirable to explore the use of such masking in early transition metal (ETM) catalysis, principally olefin polymerisation and metathesis. In particular we wish to examine how activity of such catalysts can be modified by the use of hemi-labile ligands. Triarylphosphites do not make ideal ligands for ETM complexes, as the phosphorus donor is a soft Lewis π-acid. The parent thiobis(phenoxide) of **49** has two hard π-basic oxide donor groups, ideal for coordination to electron deficient ETMs. The soft, π-acidic sulphur group will be expected to bind only weakly to the metal site in a hemi-labile fashion- thus masking highly active catalytic sites. This will give a stable, comparatively easy to handle pre-catalysts that activate in solution by de-coordination of the S-group.

5.3 Results and Discussion

5.3.1 Synthesis and characterisation of $S[(t\text{-}Bu)_2C_6H_2O]_2PCl$ (50) and $CH_2[(t\text{-}Bu)_2C_6H_2O]_2PCl$ (51)

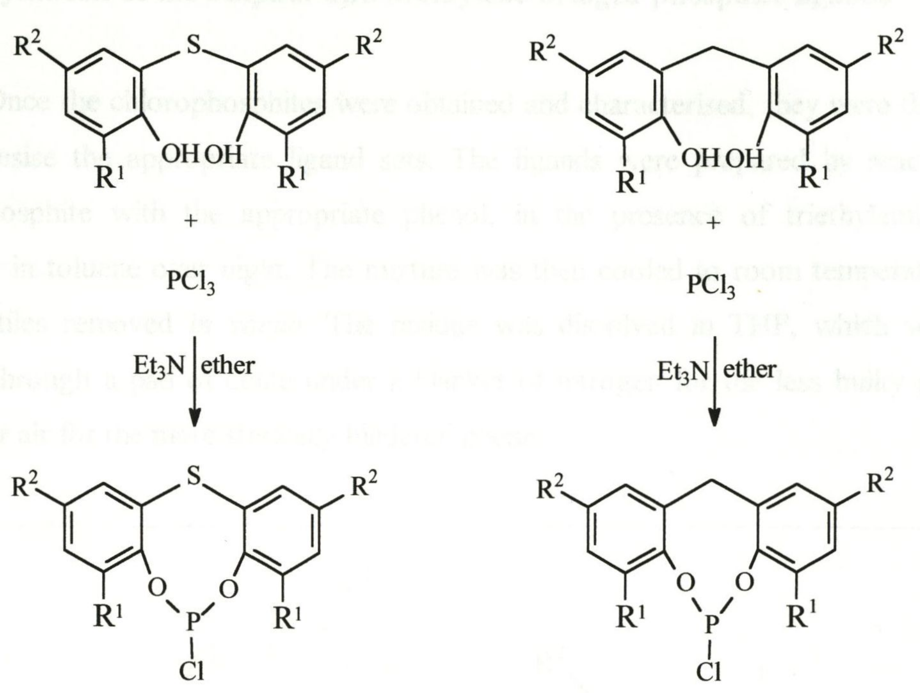
The parent diol (2,2'-thiobis(4,6-di-*t*-butylphenol) **49** and was prepared by a modification of the previously reported procedure by Pastor *et. al.*[15] A solution of the appropriate phenol and anhydrous zinc chloride dissolved in hexane as a mild Lewis acid catalyst in dry hexane was cooled to 0 °C (scheme 5.2.1). This was then treated with sulphur dichloride dissolved in hexane over a period of half an hour. Upon completion, the mixture was stirred at room temperature for 12 hours. The solvent was removed *in vacuo* and the residue was recrystallised from acetonitrile to give a fine white powder in an 82 % yield compared to 59 % that was previously reported.[15] The ^{1}H NMR was identical to that reported by Pastor.



49 $R^1 = R^2 = {}^t$Bu

Scheme 5.2.1 Syntheses of parent diols **49**

This diol was then used to synthesise the chlorophosphite ($S[(t\text{-}Bu)_2C_6H_2O]_2PCl$) **50** which follows an earlier reported procedure.[7] The chlorophosphite was prepared by treating the diol (2,2'-thiobis(4,6-di-*t*-butylphenol) **49** with phosphorus trichloride using triethylamine as an acid acceptor in diethyl ether to give the sulphur containing chlorophosphite **50** (scheme 5.2.2).[7] The ^{31}P NMR showed a singlet at 170.2 ppm.



50 $R^1 = R^2 = {}^tBu$

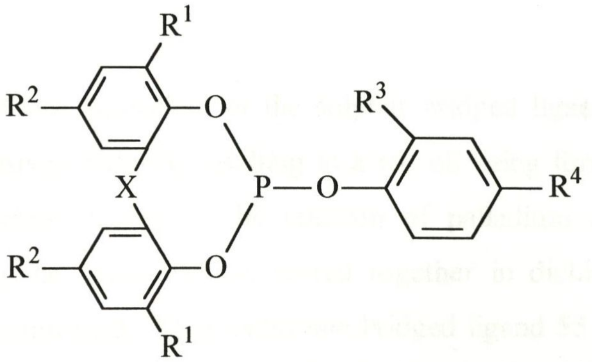
51 $R^1 = {}^tBu$, $R^2 = Me$

Scheme 5.2.2 Synthesis of the chlorophosphites **50** and **51**

For comparison of ring conformation changes the synthesis and characterisation of the chlorophosphite ($CH_2[(t\text{-}Bu)_2C_6H_2O]_2PCl$) **51** where a methylene group is present in place of a sulphur atom, was also conducted. The chlorophosphite **51** was synthesised by treatment of the parent diol (2,2'-methylenebis(4-methyl-6-*t*-butylphenol) with phosphorus trichloride in the presence of triethylamine to give the methylene bridged chlorophosphite in a 43 % yield. The ^{31}P NMR of **51** showed a singlet at δ 155.8 ppm. Due to the air sensitivity of the product **51**, the ^1H NMR has not been reported previously. With the use of sealed NMR tubes (Young's NMR tubes) it was possible to record the ^1H NMR of the compound **51** in dry $CDCl_3$. This showed a very distinctive set of doublets at δ 3.7 and 3.9 ppm, which correspond to the methylene bridge (CH_2), with one doublet representing the *endo* H and one doublet representing the *exo* H of the CH_2 group, respectively. The doublets have a coupling constant of $J = 13$ Hz each. The methylene bridge for the parent diol appears at δ 3.9 ppm as a singlet, which integrates for 2 protons.

5.3.2 Synthesis of the Sulphur and Methylene bridged phosphite ligands

Once the chlorophosphites were obtained and characterised, they were then used to synthesise the appropriate ligand sets. The ligands were prepared by reacting the chlorophosphite with the appropriate phenol, in the presence of triethylamine, and refluxing in toluene over night. The mixture was then cooled to room temperature and the volatiles removed *in vacuo*. The residue was dissolved in THF, which was then filtered through a pad of celite under a blanket of nitrogen for the less bulky phenols, but under air for the more sterically hindered phenol.



Sulphur bridged ligands

X = S

52 $R^1 = R^2 = R^3 = {}^tBu$, $R^4 = Me$

53 $R^1 = R^2 = R^3 = R^4 = {}^tBu$

Methylene bridged ligands

$X = CH_2$

54 $R^1 = R^3 = {}^tBu$, $R^2 = R^4 = Me$

55 $R^1 = {}^tBu$, $R^2 = R^3 = R^4 = Me$

56 $R^1 = R^3 = R^4 = {}^tBu$, $R^2 = Me$

The ^1H NMR of the methylene bridged triaryl phosphite ligands all exhibit a set of doublets, which correspond to the *endo*, and the *exo* hydrogen's of the methylene group and has the same coupling constant (J = 13 Hz) as the doublets of the chlorophosphite ($CH_2[(t\text{-}Bu)_2C_6H_2O]_2PCl$) **51**.

The ^{31}P NMR spectra for the phosphite ligands all show a singlet in the phosphite region with a range from δ 137 – 133 ppm. This corresponds well with the spectra for triarylphosphite ligands, for example the ^{31}P NMr for tris(2,4-di-*tert*-butylphenyl)phosphite **6** shows a singlet at δ 131 ppm. Table 5.1 lists the ^{31}P NMR peaks for each of the phosphite ligands synthesised.

Table 5.1 Comparison of δ for the triarylphosphite ligands

Complex	**52**	**53**	**54**	**55**	**56**
^{31}P NMR(ppm)	δ 137.2	δ 134.7	δ 132.9	δ 133.7	δ 133.4

5.3.3 The Formation of the Methylenebridged phosphite palladium anion complex $[Pd(Cl)_3\{(CH_2[(2\text{-}t\text{-}Bu)(4\text{-}Me)C_6H_2O]_2)P(OC_6H_32,4\text{-}Me)\}\{Et_3NH\}]$ (57)

The reaction of one equivalent of the sulphur bridged ligands **52** and **53** with palladium dichloride proved difficult, resulting in a red oil being formed with a peak at 85 ppm in the ^{31}P NMR. However, the reaction of palladium dichloride and one equivalent of triethylamine hydrochloride, stirred together in dichloromethane for 15 minutes to which one equivalent of the methylene bridged ligand **55** was added, proved successful. The mixture was stirred for a further hour during which time the solution changed to a rust brown/orange colour. The solvent was removed and anionic complex $[Pd(Cl)_3\{(CH_2[(2\text{-}t\text{-}Bu)(4\text{-}Me)C_6H_2O]_2)P(O\ C_6H_32,4\text{-}Me)\}\{Et_3NH\}]$ **57** was obtained in 95 % yield after recrystalisation from a dichloromethane/hexane mixture. The ^{31}P NMR of **57** showed a singlet at δ 79.03 ppm. Crystals of the complex **57** were grown from a dichloromethane/hexane mixture. The X-ray analysis confirms the formation of the palladium phosphite anion complex **57** with the counter ion as triethylammonium. The molecular structure is shown in Fig. 5.1 together with the labelling scheme. Selected bond lengths are listed in table 5.1. The structure consists of four $[Pd(Cl)_3\{CH2[(t\text{-}Bu)_2C_6H_2O]_2P\}\{Et_3N\}]$ molecules in the asymmetric unit. The geometry of the palladium centre is distorted square planar. It was previously reported that cyclic chlorophosphite **50** maybe regarded as psuedo trigonal bipyramids (TBP).[7] Similarly, it was found that in each case the sulphur atom which acts as a bridgehead between the two aryl components showed coordinative tendencies to the phosphorus atom which was proven by an examination of the P---S distance.[7] Also it was shown that the ring conformation was in a boat-boat conformation (*syn* arrangement).

However, this contrasts with the ring conformation for **51**, which has the same composition as **50** except for the replacement of the sulphur bridgehead atom by a methylene group. In this case the ring exhibits a boat-chair (*anti*) conformation.[8] The presence of the methylene bridgehead between the two-aryl components of the triarylphosphite in complex **57** showed the boat-chair (*anti*) conformation similar to that of the ring conformation of the previously reported **51**.

The average Pd-Cl is 2.31(4) Å this compares well with the reported average transition metal – Cl bond. The average P-O bond length is 1.58(5) Å and this compares well to that of the average P-O bond distance of 1.58(7) Å for the metallated palladium triarylphosphite complexes $[\{\overline{\mathrm{Pd}(\mu\text{-Cl})\{\mathrm{P(OC}}_6\mathrm{H}_2\text{-}2,6\text{-}{}^t\mathrm{Bu}_2)(\mathrm{OC}_6\mathrm{H}_3\text{-}2,4\text{-}{}^t\mathrm{Bu}_2)_2\}\}_2]$ **22** (Chapter 2, page 42). Likewise, the average Oxygen-Carbon (O-C) bond distance is 1.41(7) Å for the anionic complex **57** compares well with that of complex **22** which has a O-C average bond distance of 1.43(1) Å.

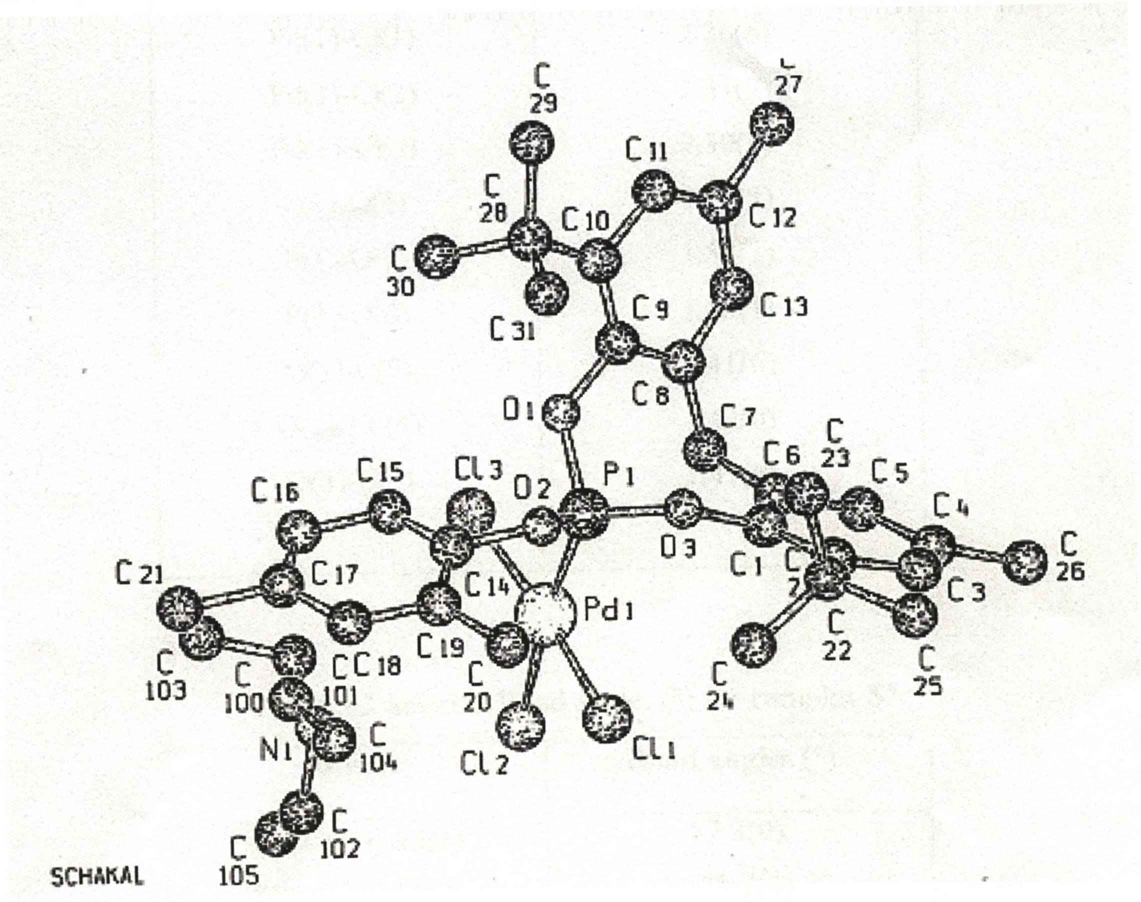


Fig 5.1 X-ray structure of the nonmetallated palladium anionic methylene bridged triarylphosphite complex $[Pd(Cl)_3\{(CH_2[(2\text{-}t\text{-}Bu)(4\text{-}Me)C_6H_2O]_2)P(O\,C_6H_32,4\text{-}Me)\}\{Et_3NH\}]$ (57)

Table 5.1 Selected Bond lengths (Å) for complex **57**

Bonds	Bond lengths (Å)
Pd(1)-P(1)	2.19(3)
Pd(1)-Cl(1)	2.26(6)
Pd(1)-Cl(2)	2.37(7)
Pd(1)-Cl(3)	2.30(1)
P(1)-O(1)	1.59(3)
P(1)-O(2)	1.58(2)
P(1)-O(3)	1.58(1)
O(1)-C(9)	1.41(6)
O(2)-C(14)	1.42(0)
O(3)-C(1)	1.41(6)

Table 5.2 Selected Bond angles (°) for complex **57**

Bonds	Bond angles (°)
P(1)-Pd(1)-Cl(1)	87.3(0)
P(1)-Pd(1)-Cl(2)	173.7(4)
P(1)-Pd(1)-Cl(3)	93.0(2)
Cl(1)-Pd(1)-Cl(3)	174.3(2)
Cl(1)-Pd(1)-Cl(2)	90.8(2)
Cl(3)-Pd(1)-Cl(2)	89.5(2)
O(1)-P(1)-O(2)	102.7(6)
O(1)-P(1)-O(3)	103.8(6)
O(2)-P(1)-O(3)	96.4(6)
O(1)-P(1)-Pd(1)	116.3(5)
O(2)-P(1)-Pd(1)	114.6(5)
O(3)-P(1)-Pd(1)	119.9(5)
C(1)-O(3)-P(1)	131.7(1)

Selected bond angles for the palladium complex **57** are listed in table 5.2. The angles around the phosphorus atom vary slightly with value of 96.4(6) ° for the angle O(2)-P(1)-O(3), while the angles O(1)-P(1)-O(2) and O(1)-P(1)-O(3) are 102.7(6) ° and 103.8(6) °, respectively. These angles are somewhat similar to those reported for the dimeric palladium triarylphosphite complex **22** whose angles were O(3)-P-O(2) 96.08°, O(3)-P-O(1) 99.4(0)° and O(2)-P-O(1) 105.6(2)°.

5.3.4 The Synthesis of the Metallated Methylene Bridged triarylphosphite Palladium Complex $[Pd(\mu\text{-}Cl)_2\{(CH_2[(2\text{-}t\text{-}Bu)(4\text{-}Me)C_6H_2O]_2)\}P(OC_6H_3\text{-}2,4\text{-}Me)]$ (58)

The metallated dimeric complex **58** was formed when the ligand **54** and palladium dichloride were refluxed in 2-methoxyethanol. The ^{31}P NMR shows a doublet at δ 127.1 ppm in a ratio of 2:1, which corresponds to the *cis-trans* conformation of the metallated complex **58**. It is similar to the ^{31}P NMR of the similar metallated complex **22** $[\{Pd(\mu\text{-}Cl)\{P(OC_6H_2\text{-}2,6\text{-}{}^tBu_2)(OC_6H_3\text{-}2,4\text{-}{}^tBu_2)_2\}\}_2]$. Crystals suitable for X-ray analysis were grown from a dichloromethane/ethanol mixture. The crystal structure proved that metallation had occurred and is grossly similar to that of the crystal structure of metallated complex **22**. However, it showed that the C(1) of the phenol ring metallated rather than the carbon of the methylene bridge C(7), therefore a 5-membered ring was formed rather than the 8-membered ring as expected. This may be attributed to the larger steric bulk around the methylene-bridged carbon (7). The molecular structure of the metallated palladium complex **58** is shown in fig 5.3 together with the labelling scheme. The structure consists of two $[Pd(\mu\text{-}Cl)_2\{(CH_2[(2\text{-}t\text{-}Bu,4\text{-}Me)C_6H_2O]_2)\}P(OC_6H_3\text{-}2,4\text{-}Me)]$ molecules in the asymmetric unit. The geometry of the palladium centre is distorted square planar. Selected bond lengths are listed in table 5.3.

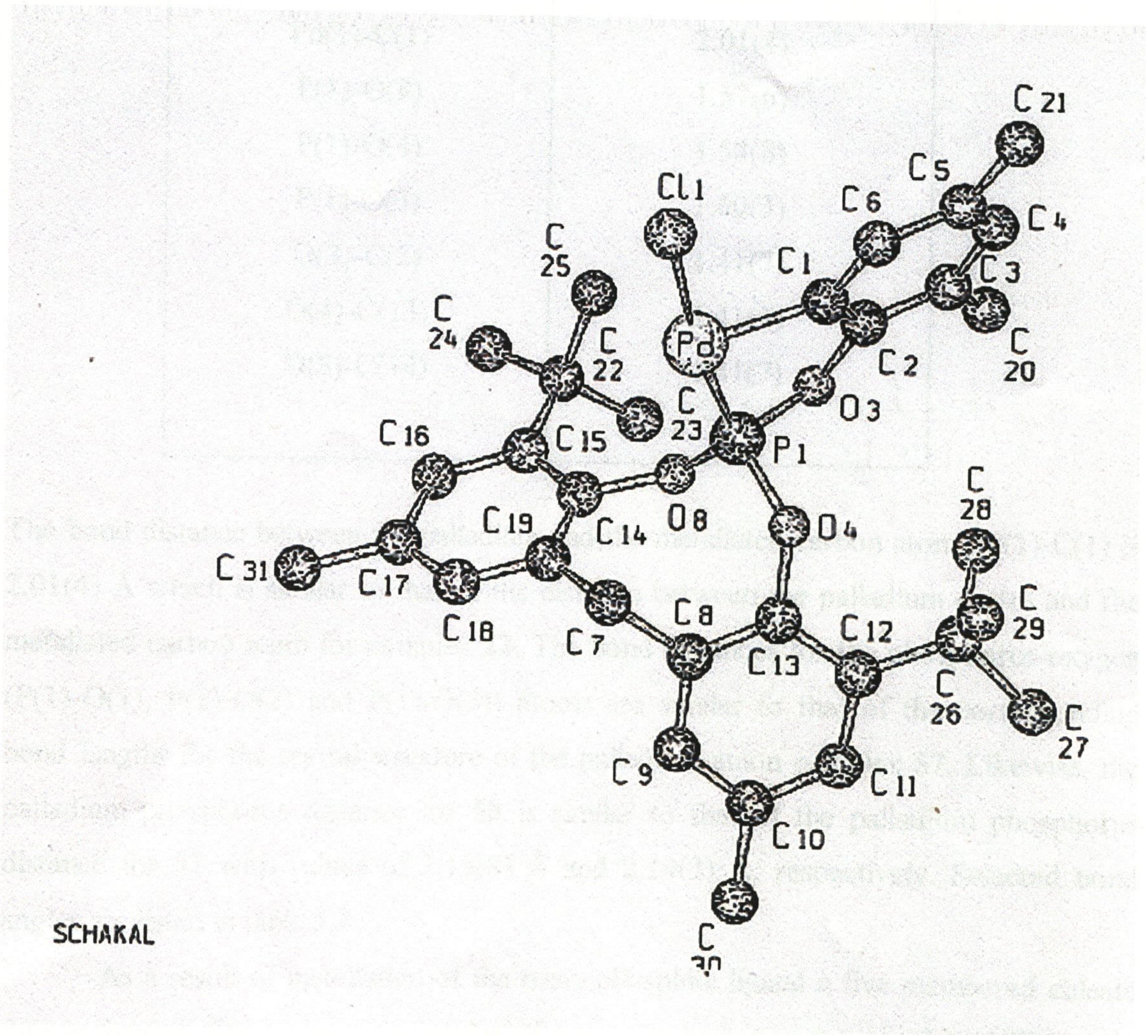


Fig 5.2 X-ray structure of the metallated palladium dimer

[Pd(μ-Cl)$_2${(CH$_2$[(2-*t*-Bu)(4-Me)C$_6$H$_2$O]$_2$) }P(OC$_6$H$_3$-2,4-Me)] (58)

Table 5.3 Selected Bond lengths (Å) for complex **58**

Bonds	Bond lengths (Å)
Pd(1)-P(1)	2.15(8)
Pd(1)-Cl(1)	2.38(9)
Pd(1)-C(1)	2.01(4)
P(1)-O(8)	1.57(6)
P(1)-O(4)	1.58(8)
P(1)-O(3)	1.60(3)
O(3)-C(2)	1.41(7)
O(4)-C(13)	1.41(1)
O(8)-C(14)	1.41(7)

The bond distance between the palladium and the metallated carbon atom Pd(1)-C(1) is 2.01(4) Å which is similar to that of the distance between the palladium centre and the metallated carbon atom for complex **22**. The bond distances for the phosphorus-oxygen (P(1)-O(1), P(1)-O(2) and P(1)-O(3)) atoms are similar to that of the corresponding bond lengths for the crystal structure of the palladium anion complex **57**. Likewise, the palladium phosphorus distance for **58** is similar to that of the palladium phosphorus distance for **57** with values of 2.15(8) Å and 2.19(3) Å, respectively. Selected bond angles are listed in table 5.4.

As a result of metallation of the triarylphosphite ligand a five membered chleate ring is formed. On a plane, the angles of a regular pentagon are equal to 107 ° each. Considering that the members of the metallated ring are almost in the same plane the slight deformations allow a smooth flexibility. The theoretical model fits well with reality. Indeed the summation of the inside angles of the pentagon is equal to 530 ° (5 x 107 ° = 535 °). However, each individual angle is not equal to 107 °, there are many variations. The C(2)-C(1)-Pd angle is imposed by the phenyl ring geometry, thus the angle is 117.9 °, instead of 107 °. As the geometry around the palladium centre is distorted square planar, the angles deviate significantly from 90 °. The C(1)-Pd-P(1) angle is 79.3 ° and is similar to the P-M-C bite angle of **22** which was found to be 81 °.

Finally, the O(3)-C(2)-C(1) angle at 115.4 ° is reduced compared to an ideal sp^2 carbon, which is 120 °.

Table 5.4 Selected Bond angles (°) for complex **58**

Bonds	**Bond angles (°)**
P(1)-Pd-C(1)	78.0(6)
C(1)-Pd-Cl(1)	94.3(8)
P(1)-Pd-Cl(1)	172.1(7)
O(8)-P(1)-O(4)	105.3(2)
O(8)-P(1)-O(3)	98.2(9)
O(4)-P(1)-O(3)	104.4(3)
O(8)-P(1)-Pd	125.5(1)
O(4)-P(1)-Pd	113.6(0)
O(3)-P(1)-Pd	106.8(3)
Pd-C(1)-C(2)	117.9(3)
C(1)-C(2)-O(3)	117.6(3)
C(2)-O(3)-P(1)	109.4(2)

5.4 Conclusion and Future work

Preliminary tests of the anionic complex **57** and the metallated complex **58** in the aqueous Suzuki coupling reaction between 4-bromoacetophenone and benzofuran-2-boronic acid, proved promising with a conversion of 60% and 54.3 % respectively with 0.0001 mol% catalysts used. As benzofuran-2-boronic acid is quite difficult to couple with aryl halides and has important industrial applications these results are very encouraging.

Due to unforeseen problems a full in-depth study of these complexes as active catalysts was not carried out. However, this work could take up a whole new project as future work with emphasis on aryl chlorides and boronic acids that are difficult to coupling with aryl halides.

5.5 Experimental

5.5.1 General Experimental

Chemicals were obtained from Aldrich and used without further purification. All solvents were dried prior to use. Reactions were carried out in flame-dried glassware under a dry nitrogen atmosphere. ^1H and ^{31}P NMR spectra were recorded on a DPX-400 Bruker (400MHz) instrument. ^1H chemical shifts are reported in ppm relative to tetramethylsilane. Chemical shifts for ^{31}P NMR (162 MHz) spectra were obtained by setting triphenylphosphine at –5.0 ppm and are referred to 85% H_3PO_4 with negative shifts upfield. All NMR spectra were obtained at 30 °C.

2,2'-Methylenebis(4,6-di-*t*-butylphenol) was purchased from Aldrich and 2,2'-Thiobis(4,6-di-*t*-butylphenol) was prepared with slight modification, which is outlined below, to procedure previously reported by Pastor *et al.*[15]

5.5.2 Synthesis of 2,2'-Thiobis(4,6-di-*t*-butylphenol) (49)

To a solution of 2,4-di-*t*-butylphenol (206.3 g, 1.0 mol) and anhydrous zinc chloride (1.02 g, 7.5 mmol) in hexane (200 ml) at 0 °C was added dropwise, over a period of half an hour, a solution of sulphur dichloride (51.5 g, 0.5 mol) in hexane (100 ml). The reaction mixture was stirred for 12 hours at room temperature with a slow nitrogen sweep to remove evolved hydrogen chloride gas. The solvent was removed *in vacuo* and the residue recrystallised from acetonitrile to give the product as a fine white powder in 82 % yield.

^1H NMR ($CDCl_3$): δ 1.25 (s, $C(CH_3)_3$, 18H), 1.45 (s, $C(CH_3)_3$, 18H), 6.48 (br s, OH, 2H), 7.18 (d, $J = 2.5$ Hz, aryl-H, 2H), 7.30 (d, $J = 2.5$ Hz, aryl-H, 2H).

5.5.3 Synthesis of $S[(t\text{-}Bu)_2C_6H_2O]_2PCl$ (50)[7]

To a stirred solution of phosphorus trichloride (1.5 ml, 17.2 mmol) in hexane (200 ml) at 0 °C was added dropwise a solution of 2,2'-thiobis(4,6-di-*t*-butylphenol) (7.6 g, 17.2 mmol) and triethylamine (5 ml, 35.97 mmol) in hexane (50 ml) over a period of one-hour. The mixture was allowed to stir at room temperature for a further 12 hours. The solution was filtered through a pad of celite and the solvent removed *in vacuo*. The residue was dissolved in dichloromethane and petroleum ether added. The solvent was reduced to half its volume after which time the product precipitated out as a fine pale yellow powder; yield (5.0 g, 58 %).

^{1}H NMR ($CDCl_3$): δ 1.34 (s, $C(CH_3)_3$, 18H), 1.48 (s, $C(CH_3)_3$, 18H), 7.43 (d, $J = 2.5$ Hz, aryl-H, 2H), 7.54 (d, $J = 2.5$ Hz, aryl-H, 2H).

^{31}P NMR ($CDCl_3$): δ 170.18 ppm.

5.5.4 Synthesis of $CH_2[(2\text{-}t\text{-}Bu)(4\text{-}Me)C_6H_2O]_2PCl$ (51)

To a stirred solution of phosphorus trichloride (1.5 ml, 17.2 mmol) in hexane (100 ml) at 0 °C was added dropwise a solution of 2,2'-methylenebis(4-methyl-6-*t*-butylphenol) (5.07 g, 14.9 mmol) and triethylamine (4.3 ml, 30.9 mmol) in hexane (100 ml) over a period of one-hour. The solution was then stirred at room temperature for 12 hours. The solution was filtered through a pad of celite and the solvent removed *in vacuo*. The residue was dissolved in dichloromethane (30 ml) and petroleum ether (20 ml) added and the solvent reduced to half its volume after which the product precipitates out as a fine yellow powder; (2.55 g, 43 % yield).

^{1}H NMR ($CDCl_3$): δ 1.40 (s, $C(CH_3)_3$ 18H), 2.3 (s, CH_3, 6H), 3.71 (d, $J = 13.1$ Hz, CH_2, 1H), 3.98 (d, $J = 13.1$ Hz, CH_2, 1H), 7.05 (d, $J = 2.5$ Hz, aryl-H, 2H), 7.1 (d, $J = 2.5$ Hz, aryl-H, 2H).

5.5.5 Synthesis of 2,2'-thiobis(4,6-di-*t*-Butylphenyl)(2-*t*-Butyl-4-methylphenyl)phosphite (52)

To a solution of $S[(t\text{-}Bu)_2C_6H_2O]_2PCl$ (**50**) (1 g, 2.0 mmols) and 2-*t*-Butyl-4-methyl phenol (0.33 g, 2.0 mmols) in toluene (20 mL) triethylamine (0.30 mL, 2.0 mols) was added dropwise. The solution was then heated at reflux for two hours after which time the solution was cooled then filtered to remove the insoluble triethlyamine hydrochloride. The solvent was removed. The residue was washed with cooled ethanol (3 x 10 mL) to yield a white powder (yield 26 %).

^{1}H NMR δ ($CDCl_3$): 1.33 (s, $C(CH_3)_3$ 18H), 1.44 (s, $C(CH_3)_3$ 27H), 2.37 (s, CH_3, 3H), 6.94 (d, *J* = 7.5 Hz, aryl-H, 1H), 7.06 (s, aryl-H, 1H), 7.21 (d, *J* = 7.5 Hz, aryl-H, 1H), 7.37 (d, *J* = 2.0 Hz, 2H), 7.54 (d, *J* = 2.0 Hz, 2H) ppm.

^{31}P NMR δ ($CDCl_3$): 137.20 ppm.

^{13}C NMR δ ($CDCl_3$): 20.11 (s, CH_3), 30.1 (d, $C(\mathit{CH_3})_3$), 34.9 (d, $\mathit{C}(CH_3)_3$ 117 (d, aryl CH), 121.9 (s, aryl CH), 125.3 (s, aryl CH), 129.2 (s, aryl CH), 131.5 (s, aryl CH), 139.6 (s, aryl CH), 145.2(s, aryl CH) ppm.

5.5.6 Synthesis of 2,2'-thiobis(4,6-di-*t*-Butylphenyl)(2,4-*t*-Butylphenyl)phosphite (53)

To a solution of $S[(t\text{-}Bu)_2C_6H_2O]_2PCl$ (**50**) (1 g, 2.0 mmols) and 2,4-di-*t*-butylphenol (0.509 g, 2.0 mmol) in diethyl ether (20 ml) was added triethylamine (0.4 ml, 2.5 mmol). The solution was then heat at reflux for 12 hours. The solution was cooled and filtered through a pad of celite. The pad of celite was washed with ether and the extracts combined. The solvent was removed under reduced pressure to a yield an impure yellow solid. This was washed with cold ethanol to yield the product as a fine white powder.

^{1}H NMR δ ($CDCl_3$): 1.48 (m, $C(CH_3)_3$ 54H), 6.64 (d, *J* = 8.0 Hz, aryl-H, 1H), 7.06 (s, aryl-H, 1H), 7.21 (d, *J* = 7.5 Hz, aryl-H, 1H), 7.37 (d, *J* = 2.5 Hz, 2H), 7.54 (d, *J* = 2.5 Hz, 2H).

^{31}P (161.9 MHz, $CDCl_3$, 293 K) δ 134.72 ppm

5.5.7 Synthesis of 2,2'-methylenebis(4-methyl-6-*t*-Butylphenyl)(2-*t*-Butyl-4-methylphenyl)phosphite (54)

To a solution of $CH_2[(2\text{-}t\text{-}Bu)(4\text{-}Me)C_6H_2O]_2PCl$ (**51**) (1 g, 2.5 mmols) and 2-*t*-Butyl-4-methyl phenol (0.41 g, 2.5 mmols) in toluene (20 mL) triethylamine (0.35 mL, 2.5 mols) was added dropwise. The solution was then heated at reflux for two hours after which time the solution was cooled then filtered to remove the insoluble triethlyamine hydrochloride. The solvent was removed. The residue was washed with cold ethanol (3 x 10 mL) to yield a white powder (yield 26 %).

^{1}H NMR δ ($CDCl_3$): 1.33 (s, $C(CH_3)_3$, 18H); 1.51 (s, $C(CH_3)_3$, 9H,); 2.31 (s, 6H, CH_3); 2.33 (s, 3H, CH_3); 3.47 (d, 1H, CH_2, J = 13.05 Hz); 4.45 (d, 1H, CH_2, J = 13.05 Hz); 6.9 (d, J = 8.0 Hz, aryl-H, 1H), 7.04 (s, aryl-H, 1H), 7.14 (s, aryl-H, 1H), 7.19 (s, aryl-H, 2H), 7.58 (d, J = 8.0 Hz, aryl-H, 2H).

^{31}P NMR δ ($CDCl_3$): 132.94 ppm

5.5.8 Synthesis of 2,2'-methylenebis(4-methyl-6-*t*-Butylphenyl)(2,4-di methylphenyl)phosphite (55)

To a solution of $CH_2[(2\text{-}t\text{-}Bu)(4\text{-}Me)C_6H_2O]_2PCl$ (**51**) (1 g, 2.5 mmols) and 2,4-dimethylphenol (0.3 mL, 2.5 mmols) in toluene (20 mL) triethylamine (0.35 mL, 2.5 mmols) was added drop-wise. The mixture was then heated to reflux and refluxed for 18 hours. The volatiles were removed *in vacuo* and the residue was extracted with THF and filtered through a pad of celite. The celite was washed with THF (3 x 10 mL), the extracts combined and the solvent was removed *in vacuo*. The residue was then washed with cold ethanol (3 x 10 mL) the yield the title compound as a white powder (yield 35%).

^{1}H NMR δ ($CDCl_3$): 1.53 (s, 18H, ^{t}Bu); 2.37 (s, 6H, CH_3); 2.87(s, 6H, CH_3); 3.75 (d, 1H, CH_2, J = 13.05 Hz); 4.42 (d, 1H, CH_2, J = 13.05 Hz); 6.82 (d, J = 8.0 Hz, aryl-H, 1H), 6.97 (s, aryl-H, 1H), 7.18 (s, aryl-H, 1H), 7.20 (s, aryl-H, 2H), 7.44 (d, J = 8.0 Hz, aryl-H, 2H).

^{31}P NMR δ ($CDCl_3$): 133.7 ppm.

5.5.9 Synthesis of 2,2'-methylenebis(4-methyl-6-*t*-Butylphenyl)(2,4-di-*t*-butylphenyl)phosphite (56)

To a solution of $CH_2[(2\text{-}t\text{-}Bu)(4\text{-}Me)C_6H_2O]_2PCl$ **(51)** (2.5g, 4.9 mmols) and 2,4-di-*t*-butylphenol (1.01 g, 4.9 mmols) in toluene (20 mL) triethylamine (1 ml, 4.9 mmols) was added drop-wise. The mixture was then heated to reflux and refluxed for 18 hours. The volatiles were removed *in vacuo* and the residue extracted with THF and filtered through a pad of celite. The celite was washed with THF (3 x 10 mL), the extracts combined and the solvent was removed in vacuo. The residue was then washed with cold ethanol (3 x 10 mL) the yield the title compound as a white powder (yield 75%)

^{1}H NMR δ ($CDCl_3$): 1.32 (s, $C(CH_3)_3$, 18H); 1.53 (s, 18H, ^{t}Bu); 2.31 (s, 6H, CH_3), 3.46 (d, $J = 12.5$ Hz, CH_2, 1H), 4.47 (d, $J = 12.5$ Hz, CH_2, 1H), 7.04 (s, aryl-H, 2H), 7.14 (br, s, aryl-H, 3H), 7.41 (s, aryl-H, 1H), 7.56 (d, $J = 6.5$ Hz, aryl-H, 1H) ppm.

^{31}P NMR δ ($CDCl_3$): 133.49 ppm.

^{13}C NMR δ ($CDCl_3$): 20.56 (s, CH_3), 30.3 ($C(CH_3)_3$), 34.83 (d, CH_2), 33.98 (d, CH_2), 122.8 (s, aryl CH), 123.7 (s, aryl CH), 126.2 (s, aryl CH), 128.2 (s, aryl CH), 133.2 (s, aryl CH), 135.5 (s, aryl CH), 145.4 (s, aryl CH) ppm aromatic.

5.5.10 The Formation of the Methylenebridgedphosphite palladium anion complex $[Pd(Cl)_3\{(CH_2[(2\text{-}t\text{-}Bu)(4\text{-}Me)C_6H_2O]_2)P(O\ C_6H_3\text{-}2,4\text{-}Me)\}\{Et_3NH\}]$ (57)

A mixture of palladium dichloride (0.10 g, 0.56 mmol) and triethylamine hydrochloride (0.078 g, 0.56 mmol) were stirred together at room temperature for 15 minutes. To this mixture tris(2,4-di-*t*-butylphenylphosphite) (0.36 g, 0.56 mmol) was added and the mixture stirred for an hour. During which time the solution changes from a pale yellow to a rust brown colour. The solvent was removed *in vacuo* and the residue recrystalised form a dichloromethane/hexane mix to yield the product as a fine yellow powder in 95 % yield.

^{1}H NMR δ ($CDCl_3$): δ 1.28 (s, 18H, $(CH_3)_3$); 1.40 (t, CH_3, Et_3N); 3.08 (q, CH_2, Et_3N); 3.41 (s, CH_2, 1H); 4.23 (s, CH_2, 1H); 7.1 (d, *H*-aryl, J = 8.0 Hz); 7.34 (s, *H*-aryl); 7.99 (d, *H*-aryl, J = 8.0 Hz); 7.4 (d, *J* = 2.0 Hz, 2H), 7.64 (d, *J* = 2.0 Hz, 2H) ppm.

^{31}P NMR δ ($CDCl_3$): 79.03 ppm

5.5.11 The Synthesis of the Metallated Methylene Bridged triarylphosphite Palladium Complex [Pd(μ-Cl)$_2${(CH_2[(2-*t*-Bu)(4-Me)C_6H_2O]$_2$)}P(OC_6H_3-2,4-Me)] (58)

A suspension of ligand **54** (0.300g, 0.564 mmol) and $PdCl_2$ (0.100g, 0.564 mmol) in 2-methoxyethanol (7 ml) was heated at reflux for 2 hours during which time the colour changed from rust brown to pale yellow, some deposition of palladium metal was also observed. The mixture was then allowed to cool and the solvent removed *in vacuo*. The residue was extracted with dichloromethane (10 ml) and the resultant solution filtered through a pad of celite. The combined dichloromethane extracts were concentrated *in vacuo* and ethanol (5 ml) was added. Subsequent concentration and addition of ethanol lead to the precipitation of product as pale orange microcrystals (Yield 85 %).

^{1}H NMR δ ($CDCl_3$): 1.35 (s, $C(CH_3)_3$, 18H); 1.48 (s, $C(CH_3)_3$, 18H,); 2.31 (s, 12H, CH_3); 2.33 (s, 12H, CH_3); 3.42 (d, 2H, CH_2, *J* = 13.05 Hz); 3.24 (d, 2H, CH_2, *J* = 13.05 Hz); 6.7 (d, *J* = 8.0 Hz, aryl-H, 2H), 7.06 (m, aryl-H, 10H) ppm.

^{31}P NMR δ ($CDCl_3$): 127.1 and 126.3 ppm

5.6 References

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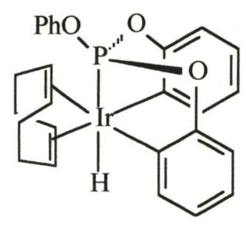
Chapter 6

Future Work

6.1 Iridium Chemistry.

The use of orthometallated triarylyphosphite complexes in catalysis remains a somewhat under-exploited field. Lewis showed that a range of orthometallated triarylphosphite complexes of the type $[L_nM\{P(OC_6H_3R)(OC_6H_4R)\}]$ (M = Ru, Co, Pd) are more effective catalysts than the non-metallated analogoues in the hydrogenation of alkenes and alkynes.[1] Later he demonstrated that orthometallated triphenylphosphite ruthenium complexes catalyse the selective ortho-deuteration[2] and –ethylation[3] of phenol. We have shown that the bulky triarylphosphite tris(2,4-di-*tert*-butylphenyl)phosphite, **6**, orthometallated at palladium to give a catalyst that shows extremely high activity in biaryl coupling reactions under Suzuki and Stille conditions[4] and in the Heck arylation of alkenes.[5] It has been previously reported that **6**, readily di-orthometallates at iridium to give the hydrogenation catalyst **10.**[6] By comparison, the triphenylphosphite complex **3** showed very poor catalytic activity, despite the fact that this species is iridium(I) and thus more likely to undergo oxidative-addition reactions.



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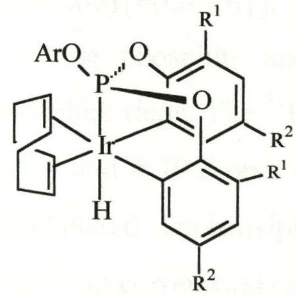
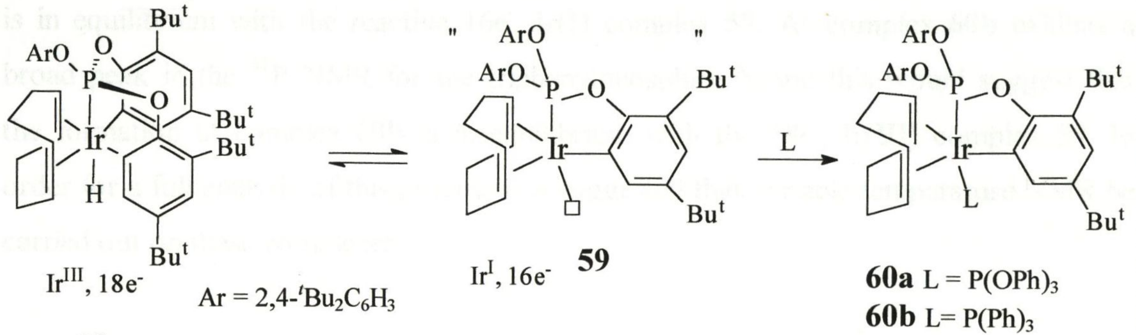


10

6.1.2 Results and Discussion

We suggested therefore, that the 18e, Ir(III) complex **10** probably undergoes an activation process prior to reaction with H_2 and subsequent generation of an active catalytic species. We proposed that this activation is probably the reductive-elimination of one of the aryl ligands and the hydride to generate a 16e iridium (I) species **59** (scheme 6.1), which is then able to react with hydrogen to form an active catalyst. In effect, the second orthometallation could be described as 'masking' the reactive species

59. If such an activation pathway does indeed exist then it should be possible to trap 'unmasked' **59** by reaction with appropriate ligands to generate the adduct **60**. This is a report of the preliminary findings of such reactions.



10 **59** **60a** L = $P(OPh)_3$ **60b** L= $P(Ph)_3$

Scheme 6.1 Proposed route to the formation of **59**

The reaction of **10** with triphenylphosphite leads to the formation of the colourless complex $[Ir\{P(OC_6H_2\text{-}2,4\text{-}Bu^t_2)(OC_6H_3\text{-}2,4\text{-}Bu^t_2)_2\}(cod)\{P(OPh)_3\}]$, **60a** presumably due to the considerably low steric hindrance of the phosphite and the facile de-orthometallation of one of the metallated triarylphosphite rings. The ^{31}P NMR spectrum shows a typical AB system with doublets at δ 125.4 and δ 79.2 ppm corresponding to the metallated triarylphosphite and the non-metallated triphenylphosphite ligands respectively with a $^2J_{(PP)}$ coupling of δ 69.5 Hz. This data corresponds closely to that for $[IrH\{P(OC_6H_4)(OC_6H_5)_2\}\{P(OC_6H_5)_3\}(cod)]$ **4** which also shows an AB system with doublets at δ 126.2 and δ 83.1 ppm and a $^2J_{(PP)}$ coupling of 83.1 Hz.[6] This implies that there is little electronic differences between analogous phosphorus atoms in **3** and **60a** and that the geometries of the two complexes are grossly similar. It seems, therefore, that the formation of a stable mono-metallated bis-phosphite adduct such as **10** is dictated purely by the steric bulk of the phosphite ligand.

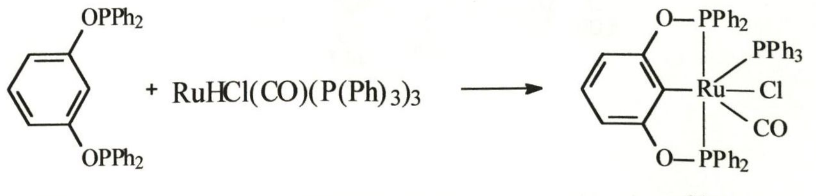
Similarly the reaction of **10** with the somewhat more bulky triphenylphosphine ligand also leads to the formation of an adduct: $[Ir\{P(OC_6H_2\text{-}2,4\text{-}Bu^t_2)(OC_6H_3\text{-}2,4\text{-}Bu^t_2)_2\{(cod)(PPh_3)]$, **60b**. The ^{31}P NMR spectrum shows a typical AB system with doublets at δ 127.9 and a broad peak at δ –11.9 ppm corresponding to the metallated triarylphophite and the non-metallated triphenylphosphine ligands respectively with a $^{2}J_{(PP)}$ coupling of 44.6 Hz.

6.1.3 Conclusion

In conclusion we have demonstrated that in solution the 18e^{-}, Ir(III) complex **10** is in equilibrium with the reactive 16e^{-}, Ir(I) complex **59**. As complex **60b** exhibits a broad peak in the ^{31}P NMR for the triphenylphosphine ligand this would suggest that the formation of complex **60b** is in equilibrium with the 18e^{-}, Ir(III) complex **59**. In order for a full analysis of this process it is suggested that variable temperature NMR be carried out on these complexes.

6.2 Ruthenium Chemistry

The reaction of the resorcinolbis(diphenyl)phosphinite, **39a** 'PCP' phosphinite ligand with $RuHCl(CO)(P(Ph)_3)_3$ in toluene leads to the metallation of the pincer ligand to give the complex **61**. The ^{31}P NMR shows a doublet at δ 147.9 ppm with a coupling of J = 12.4 Hz and a triplet at δ 19.05 ppm with a coupling constant of J = 12.4 Hz. Crystals were grown and the X-ray structure of the complex proves that metallation has occurred. The molecular structure is shown in fig 6.1 together with the labelling scheme.



39a

61

Scheme 6.2 The formation of the 'PCP'-pincer Ruthenium complex **61**

As the reaction of the 'PCP'-pincer ligand, **39a** proved positive with RuHCl(CO)(P(Ph)$_3$)$_3$ the next step is to examine the reaction of the corresponding orcinolbis(diphenyl)phosphinite), **39b** ligand.

Similarly the synthesis of other phosphinite ligands is also another possibility for future work. Once this is done then the palladium 'PCP'-pincer phosphine analogues could be tested and compared to the reactivity of the palladium 'PCP'-pincer phosphinite complexes as described in Chapter 4.

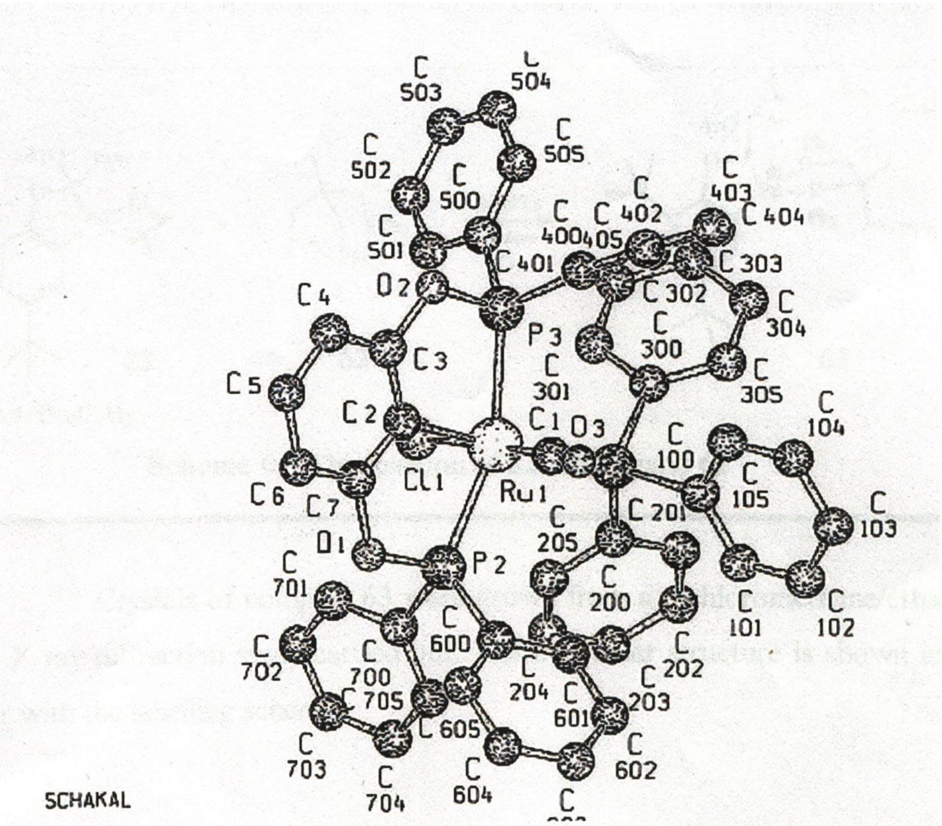
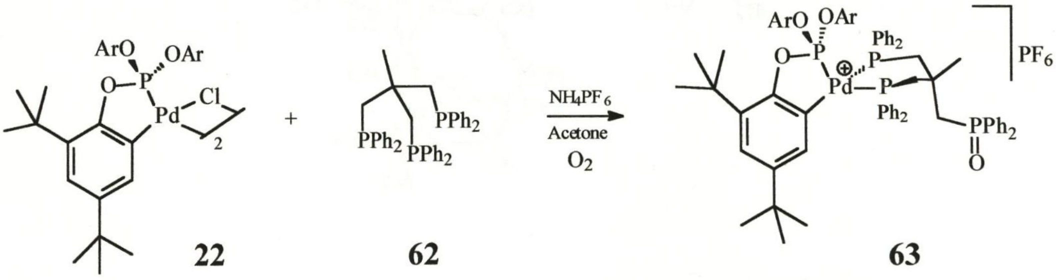


Fig. 6.1 **X-ray structure of the metallated 'PCP'-pincer Ruthenium complex (61)**

6.3 The reaction of the palladium dimer 22 with tripodal ligands

Preliminary results show that the palladium dimer [{Pd(μ-Cl){P(OC$_6$H$_2$-2,6-^{t}Bu$_2$)(OC$_6$H$_3$-2,4-^{t}Bu$_2$)$_2$}}$_2$] **22** reacts with the tripodal ligand **62** to give the cationic species **63**. The ^{31}P NMR shows a three sets of double doublets at δ 1.98, 20.1 and 140.2 with a $^1J_{(PP)}$ coupling of 32.6 Hz, $^2J_{(PP)}$ coupling of 29.7 Hz, $^1J_{(PP)}$ coupling of 62.0 Hz, $^2J_{(PP)}$ coupling of 503.6 Hz and $^1J_{(PP)}$ coupling of 32.2 Hz, $^2J_{(PP)}$ coupling of 503.6 Hz respectively. Due to the steric bulk imposed by the ^{t}butyl ligands the third phosphorus atom coordinates weakly and in solution is in equilibrium with the tri coordinated and di-coordinated tripodal.



22 **62** **63**

Ar = 2,4-^{t}Bu$_2$C$_6$H$_3$

Scheme 6.3 The reaction of **22** with ligand **62**

Crystals of complex **63** were grown from a dichloromethane/ethanol mix and the X-ray diffraction study carried out. The molecular structure is shown in fig 6.2 together with the labelling scheme.

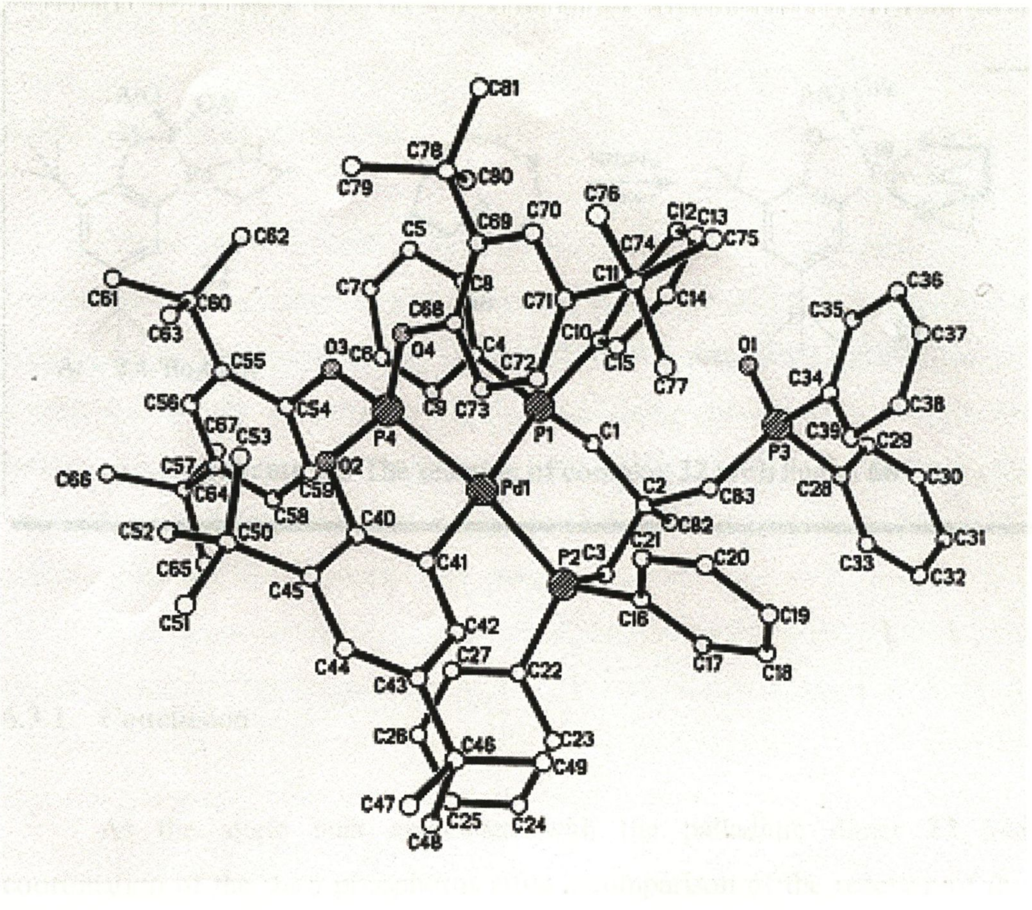
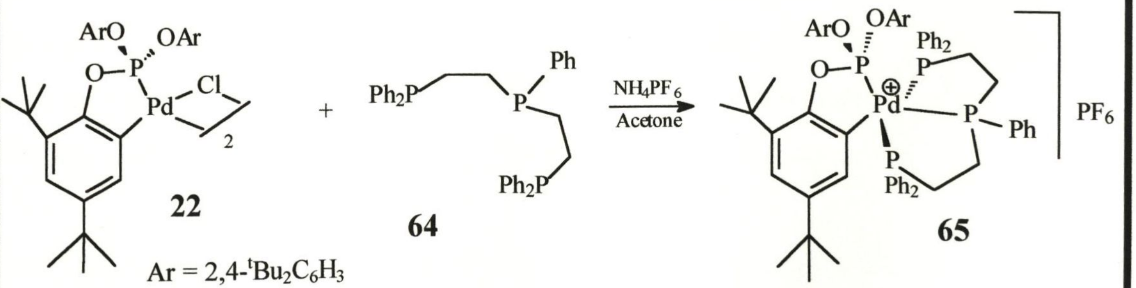
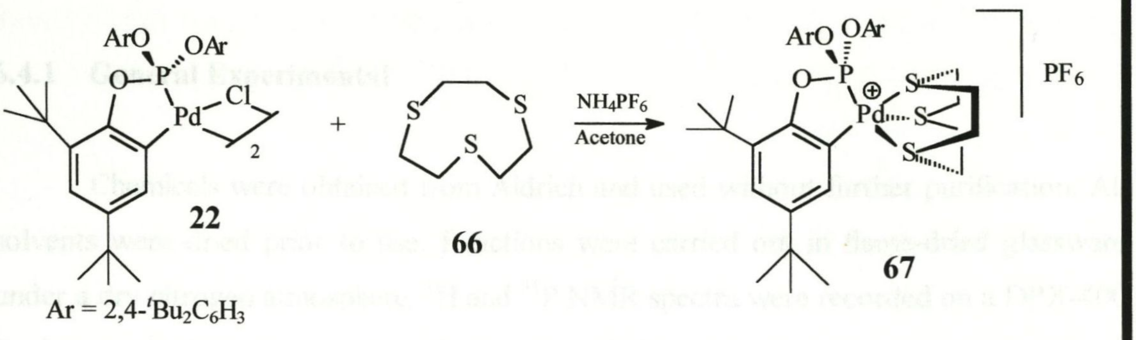


Fig. 6.2 **The X-ray stucture of complex (63)**

This could be extended to the reaction of complex **22** with other tripodal ligands **64** and **66** such as shown in schemes 6.4 and 6.5 respectively.



Scheme 6.4 The reaction of complex **22** with the tripodal ligand **64**



Scheme 6.5 The reaction of complex **22** with ligand **66**

6.3.1 Conclusion

As the steric bulk associated with the palladium dimer **22** inhibits the coordination of the third phosphorus atom a comparison of the reaction of the tripodal ligands with the metallated triphenylphosphite and triphenylphosphine analogues of **22** should show the full coordination of all the three phosphorus atoms.

6.4 Experimental

6.4.1 General Experimental

Chemicals were obtained from Aldrich and used without further purification. All solvents were dried prior to use. Reactions were carried out in flame-dried glassware under a dry nitrogen atmosphere. ^{1}H and ^{31}P NMR spectra were recorded on a DPX-400 Bruker (400MHz) instrument. ^{1}H chemical shifts are reported in ppm relative to tetramethylsilane. Chemical shifts for ^{31}P NMR (162 MHz) spectra were obtained by setting triphenylphosphine at –5.0 ppm and are referred to 85% H_3PO_4 with negative shifts upfield. All NMR spectra were obtained at 30 °C.

The tripodal ligands, 1,1,1-tris(diphenylphosphinomethyl)ethsne **62**, bis(2-diphenylphosphinoethyl)phenylphosphine **64** and 1,4,7-trithiacyclononane **66**, were purchased from Aldrich and 2,2'-$[IrH\{P(OC_6H_2\text{-}2,6\text{-}{}^tBu_2)_2(OC_6H_3\text{-}2,4\text{-}{}^tBu_2)\}(cod)]$ was prepared following the procedure previously reported by Chaloner *et al.*[15] The resorcinolbis(diphenyl)phosphinite, **39a** 'PCP' phosphinite ligand was prepared as described in chapter 4.

6.4.2 Reaction of $[IrH\{P(OC_6H_2\text{-}2,6{}^tBu_2)_2(OC_6H_3\text{-}2,4\text{-}{}^tBu_2)\}(cod)]$ with PPh_3

Triphenylphosphine (0.014 g, 0.053 mmol) was added to a stirred solution of $[IrH\{P(OC_6H_2\text{-}2,6\text{-}{}^tBu_2)_2(OC_6H_3\text{-}2,4\text{-}{}^tBu_2)\}(cod)]$ (0.05 g, 0.053 mmol) in dichloromethane. The mixture was stirred for 3 hours after, which time a white precipitate formed. The supernatant was removed with a syringe. The residue was washed with dichloromethane and dried in *vacuo* yielding a white solid.
(Yield 0.057 g, 90%)

^{31}P (161.9 MHz, $CDCl_3$, 293 K) δ –11.90 (d, *P*Ph$_3$, J_{PP} = 44.6 Hz); 127.89 (d, *P*OAr, J_{PP} = 44.6 Hz) ppm.

^{1}H NMR (400 MHz, $CDCl_3$, 293 K) δ 1.28 (s, 36H, *^{t}Bu*); 1.34 (s, 9H, *^{t}Bu*); 1.60 (s, 9H, *^{t}Bu*); 2.19 (m, 2H, cod alkane); 2.27 (m, 2H, cod alkane); 2,51 (m, 2H, cod alkane); 2.94 (m, 2H, cod alkane); 3.87 (m, 2H, cod alkene); 4.24 (m, 2H, cod alkene); 7.15 (dd, 1H, *m*-aryl of free ring, $^{3}J_{HH}$ = 8.6 Hz, $^{4}J_{HH}$ = 2.5 Hz); 7.33 (m, 15H, PPH_3); 7.49 (dd, 1H, *m*-aryl of free ring, $^{4}J_{HH}$ = 2.4 Hz, $^{5}J_{PH}$ = 1.2 Hz); 7.66 (dd, 1H, *o*-aryl of free ring $^{3}J_{HH}$ = 8.6 Hz, $^{5}J_{HH}$ = 1.4 Hz); 7.72 (d, 2H, *m*-aryl of metallated ring, $^{4}J_{HH}$ = 2.2 Hz) ppm.

6.4.3 Reaction of [IrH{P(OC$_6$H$_2$-2,6-^{t}Bu$_2$)$_2$(OC$_6$H$_3$-2,4-^{t}Bu$_2$)}(cod)] with P(OPh)$_3$

Triphenylphosphite (0.013 ml, 0.049 mmol) was added to a stirred solution of [IrH{P(OC$_6$H$_2$-2,4-^{t}Bu$_2$)$_2$(OC$_6$H$_2$-2,4-^{t}Bu$_2$)}(cod)] (0.047 g, 0.049 mmol) in dichloromethane and the mixture allowed to stir overnight. The solvent was removed under reduced pressure and the residue washed with a small amount of cold dichloromethane yielding a white solid.
(Yield 0.049 g, 80%)

^{31}P (161.9 MHz, CDCl$_3$, 293 K) δ 79.16 (d, *P*(OPh$_3$), J_{PP} = 69.4 Hz); 125.40 (d, *P*OAr J_{PP} = 69.4 Hz) ppm.

^{1}H NMR (400 MHz, CDCl$_3$, 293 K) δ 1.28 (s, 36H, *^{t}Bu*); 1.34 (s, 9H, *^{t}Bu*); 1.60 (s, 9H, *^{t}Bu*); 2.19 (m, 2H, cod alkane); 2.27 (m, 2H, cod alkane); 2,51 (m, 2H, cod alkane); 2.94 (m, 2H, cod alkane); 3.87 (m, 2H, cod alkene); 4.24 (m, 2H, cod alkene); 7.15 (dd, 1H, *m*-aryl of free ring, $^{3}J_{HH}$ = 8.6 Hz, $^{4}J_{HH}$ = 2.5 Hz); 7.43 (m, 15H, P(OPh_3)); 7.49 (dd, 1H, *m*-aryl of free ring, $^{4}J_{HH}$ = 2.4 Hz, $^{5}J_{PH}$ = 1.2 Hz); 7.66 (dd, 1H, *o*-aryl of free ring $^{3}J_{HH}$ = 8.6 Hz, $^{5}J_{HH}$ = 1.4 Hz); 7.72 (d, 2H, *m*-aryl of metallated ring, $^{4}J_{HH}$ = 2.2 Hz) ppm.

6.4.4 Synthesis of the ‘PCP’-pincer Ruthenium complex (61)

A mixture of resorcinolbis(diphenyl)phosphinite, **39a** (0.22 g, 0.44 mmols) and RuH(CO)Cl(PPh$_3$)$_3$ (0.38 g, 0.44 mmols) was refluxed under nitrogen for 2 days during which time the solution changed to yellow. The solvent was removed in *vacuo* and the residue recrystallised from DCM/Hexane to give a fine yellow powder. (Yield 0.35 g, 87 %).

^{31}P (161.9 MHz, $CDCl_3$, 293 K) δ 19.05 (t, $J = 12.4$ Hz, *P*Ph_3); 147.0 (d, $J = 12.4$ Hz, *P*(OPh_2) ppm.

^{1}H NMR (400 MHz, $CDCl_3$, 293 K) δ 6.86 (d, 2H, $^{2}J_{HH} = 8.0$ Hz, 3,5-Hs of resorcinol ring); 6.96 (t, $^{3}J_{HH} = 8.0$ Hz, 5-H of resorcinol ring);7.19 (m,15H, PPh_3); 7.33 (m, 12H, PPh_2); 7.50 (m, 8H, PPh_2) ppm.

6.4.5 Reaction of [{Pd(μ-Cl){P(OC_6H_2-2,6-^{t}Bu_2)(OC_6H_3-2,4-^{t}Bu_2)$_2$}}$_2$] and the Tripodal ligand 62

To a stirred solution of palladium dimmer **22** (0.20 g; 0.25 mmols) and tripodal ligand **62** (0.156 g; 0.25 mmols) in THF (10 mls), ammonium hexafluorophosphate (0.041 g; 0.25 mmols) was added. The mixture was stirred at room temperature for 1 hour during which time a white precipitate was formed. The solvent was removed in *vacuo* and the residue recrystallised from DCM/Hexane to give a fine white powder. (Yield 0.18 g, 94%)

^{31}P (161.9 MHz, $CDCl_3$, 293 K) δ 1.53 (q, *P*Ph_2 $J = 29.71$ Hz); 16.9 (dd, *P*Ph_2, $J = 64.4$ Hz, $J = 545.4$ Hz); 34.2 (s, O*P*Ph_2); 136.8 (dd, *P*(Oar), $J = 29.71$ Hz, $J = 545.4$ Hz) ppm.

^{1}H NMR (400 MHz, $CDCl_3$, 293 K) δ 0.933 (t, CH_3 $J = 2$ Hz); 1.23 (s, 36H, *^{t}Bu*); 1.24 (s, 18H, *^{t}Bu*); 1.35 (s, 18H, *^{t}Bu*); 1.41 (s, 36H, *^{t}Bu*); 2.5 (q, CH_2, $J = 2$ Hz); 6.94 (dd, 4H, 6-free rings, $^{3}J_{HH} = 8.5$ Hz, $^{5}J_{HH} = 2.5$ Hz); 7.08 (s, br, 3H, *H3* or *H5*-metallated rings);7.31 (m, PPh_2); 7.37 (d, 4H, *H3*-free rings $^{5}J_{HH} = 2.4$ Hz); 7.52 d, br, 2H, *H3* of *H5*-metallated rings, $^{5}J_{HH} = 5$ Hz) and 7.56 (d, 4H, *H5*-free rings, $^{3}J_{HH} = 9.0$ Hz) ppm.

6.4.6 Reaction of $[\{Pd(\mu\text{-}Cl)\{P(OC_6H_2\text{-}2,6\text{-}{}^tBu_2)(OC_6H_3\text{-}2,4\text{-}{}^tBu_2)_2\}\}_2]$ and the Tripodal ligand 64

To a stirred solution of palladium dimer **22** (0.20 g; 0.25 mmols) and tripodal ligand **64** (0.134 g; 0.25 mmols) in THF (10 mls), ammonium hexafluorophosphate (0.041 g; 0.25 mmols) was added. The mixture was stirred at room temperature for 1 hour during which time a white precipitate was formed. The solvent was removed in vacuo and the residue recrystallised from DCM/Hexane to give a fine white powder. (Yield 0.29 g, 90%)

^{31}P (161.9 MHz, $CDCl_3$, 293 K) δ – 11.39 (broad signal, free *P*Ph) 28.7 (dd, $J = 34.3$ Hz, $J = 161.27$); 74.3 (broad signal, coordinated *P*Ph); 133.08 (q, *P*OAr, $J = 34.3$ Hz, $J = 161.27$) ppm.

^{1}H NMR (400 MHz, $CDCl_3$, 293 K) δ 1.23 (s, 36H, *^{t}Bu*); 1.24 (s, 18H, *^{t}Bu*); 1.35 (s, 18H, *^{t}Bu*); 1.41 (s, 36H, *^{t}Bu*); 2.63 (m, CH_2, 4H); 2.88(m, CH_2, 4H); 6.94 (dd, 4H, 6-free rings, $^{3}J_{HH} = 8.5$ Hz, $^{5}J_{HH} = 2.5$ Hz); 7.08 (s, br, 3H, *H3* or *H5*-metallated rings); 7.31 (m, P*Ph*$_2$, 15H); 7.37 (d, 4H, *H3*-free rings $^{5}J_{HH} = 2.4$ Hz); 7.52 d, br, 2H, *H3* of *H5*-metallated rings, $^{5}J_{HH} = 5$ Hz) and 7.56 (d, 4H, *H5*-free rings, $^{3}J_{HH} = 9.0$ Hz) ppm.

6.4.7 Reaction of $[\{Pd(\mu\text{-}Cl)\{P(OC_6H_2\text{-}2,6\text{-}{}^tBu_2)(OC_6H_3\text{-}2,4\text{-}{}^tBu_2)_2\}\}_2]$ and the Tripodal ligand 66

To a stirred solution of palladium dimer **22** (0.20 g; 0.25 mmols) and tripodal ligand **66** (0.046 g; 0.25 mmols) in THF (10 mls), ammonium hexafluorophosphate (0.041 g; 0.25 mmols) was added. The mixture was stirred at room temperature for 1 hour during which time a yellow precipitate was formed. The solvent was removed in vacuo and the residue recrystallised from DCM/Hexane to give a fine yellow powder. (Yield 0.21 g, 76%)

^{31}P (161.9 MHz, $CDCl_3$, 293 K) δ 131.2 (s, *P*(OAr)) ppm.

^{1}H NMR (400 MHz, $CDCl_3$, 293 K) δ 1.23 (s, 36H, ^{t}*Bu*); 1.24 (s, 18H, ^{t}*Bu*); 1.35 (s, 18H, ^{t}*Bu*); 1.41 (s, 36H, ^{t}*Bu*); 2.6 (dd, CH_2, 6H, J = 7.5 Hz); 3.0 (dd, CH_2, 6H, J = 7.5 Hz); (6.94 (dd, 4H, 6-free rings, $^3J_{HH}$ = 8.5 Hz, $^5J_{HH}$ = 2.5 Hz); 7.08 (s, br, 3H, *H3* or *H5*-metallated rings); 7.37 (d, 4H, *H3*-free rings $^5J_{HH}$ = 2.4 Hz); 7.52 d, br, 2H, *H3* of *H5*-metallated rings, $^5J_{HH}$ = 5 Hz) and 7.56 (d, 4H, *H5*-free rings, $^3J_{HH}$ = 9.0 Hz) ppm.

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Appendices

Appendix 1

Publications

1) D. A. Albisson, R. B. Bedford and P. N. Scully, *Tetrahedron Lett.*, **1998**, 39, 9796.

2) D. A. Albisson, R. B. Bedford, S. E. Lawrence and P. N. Scully, *Chem. Commun.*, **1998**, 2095.

3) R. B. Bedford, S. M. Draper, P. N. Scully and S. L. Welch, *New J. Chem.*, **2000**, 24, 745.

Pergamon

Tetrahedron Letters 39 (1998) 9793–9796

TETRAHEDRON
LETTERS

Orthopalladated triarylphosphite complexes as highly efficient catalysts in the Heck reaction

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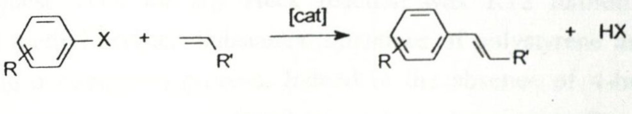
Abstract. An orthopalladated complex of commercially available tris(2,4-di-*tert*-butylphenyl)phosphite proves to be an extremely active catalyst in the Heck arylation of alkenes, with turnover numbers of up to 5,750,000 (mol product.mol Pd^{-1}) and turnover frequencies of up to nearly 300,000 (mol product.mol $Pd^{-1}.h^{-1}$).

Keywords: Heck reactions; metalation; palladium and compounds; catalysis

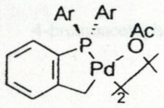
The exploitation of orthometallated triarylphosphite complexes in catalysis has so far been limited to a few reductions[1,2] and only two examples of catalytic C-C bond formation.[3,4] An important class of C-C bond forming reactions is the Heck arylation of alkenes (Scheme 1). Generally, this reaction requires fairly high catalyst concentrations (1-10mol%) limiting its attractiveness to large scale commercial applications. Consequently there has recently been an interest in developing high activity catalysts that can be used in low concentrations.

Scheme 1



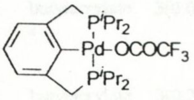
PII: S0040-4039(98)02175-3

Herrmann has reported the use of the Pd(II) complex **1** with metallated tris(2-methylphenyl)phosphine and related compounds as highly efficient catalysts for this reaction.[5] Similarly, the orthopalladated complex **2** and related species have recently been shown to be active catalysts,[6] as have palladacyclic trinapthylphosphine complexes.[7] We have recently demonstrated that the orthopalladated triarylphosphite complex **3** is an extremely active catalyst in Suzuki and Stille biaryl coupling reactions giving for the first time turnover numbers (TONs) of up to 1,000,000 (mol product.mol Pd^{-1}) and turnover frequencies (TOFs) of over 800,000 (mol product.mol Pd^{-1}.h^{-1}).[4] We report here the application of **3** to the Heck reaction. For comparison purposes we also investigated the use of the triphenylphosphine adduct of **3**, **4**, and the previously reported orthopalladated dimethylbenzylamine complex **5**.[8]

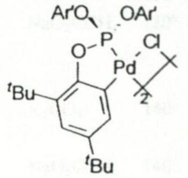


Ar = 2-MeC$_6$H$_4$

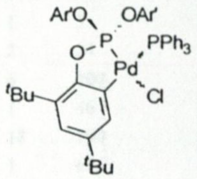
1



2

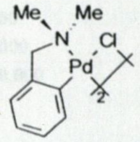


3



Ar′ = 2,4-^{t}Bu$_2$C$_6$H$_3$

4



5

Representative preliminary results for the use of **3**, **4** and **5** in the coupling of aryl bromides with *n*-butylacrylate and styrene are summarised in table 1. Examining the coupling between butylacrylate and 4-bromoacetophenone we make the following observations. Catalytic activity becomes evident at about 110°C when sodium acetate is employed as the base and increases significantly with temperature, giving TONs of up to 1,000,000 and maximum TOFs of up to at least 190,000. The use of triethylamine as base inhibits catalytic activity up to 140°C, however, activity is restored if the temperature is increased. A highly surprising result is that **3** catalyses the coupling even under air, albeit with somewhat reduced activity, demonstrating that this is a very robust system.

The highest activity was observed in the coupling of 4-bromoacetophenone with styrene with turn over frequencies of up to 290,000 observed and turn over numbers of up to 5.75 million. The previous highest TON for any Heck reaction was 1.12 million in the coupling of iodobenzene with methylacrylate.[7] Substantial quantities of polystyrene are formed during this reaction suggesting a competing process. Indeed in the absence of 4-bromoacetophenone, a mixture of **3** and sodium acetate was found to catalyse oligostyrene formation. This is not an unprecedented phenomenon - orthometallated triarylphosphite ruthenium complexes have also been shown to catalyse oligostyrene formation.[3]

Table 1

Heck arylation of alkenes catalysed by orthopalladated triarylphosphite and arylamine complexes[a]

Aryl bromide	alkene	Catalyst (mol% Pd)	Base	T (°C)	Time (hrs)	Conversion (%)[b]	TON (mol product/mol Pd)
4-bromoacetophenone	butylacrylate	3(0.2)	NaO_2CCH_3	110	1	2	10
4-bromoacetophenone	butylacrylate	3(0.2)	NaO_2CCH_3	140	1	42	210
					20	100	500
4-bromoacetophenone	butylacrylate	3(0.2)	NaO_2CCH_3	180[c]	1	100	500
4-bromoacetophenone	butylacrylate	3(0.2)	NEt_3	140	1	0	0
				180[c]	1	94	470
4-bromoacetophenone	butylacrylate	3(0.0001)	NaO_2CCH_3	180[c]	1	5	50,000
	[d]				2	24	240,000
					6	100	1,000,000
4-bromoacetophenone	butylacrylate	3(0.2)	K_2CO_3	140	1	46	230
					18	100	500
4-bromoacetophenone	styrene	3(0.2)	NaO_2CCH_3	140	1	63	315
					24	100	500
4-bromoacetophenone	styrene	3(0.0001)	NaO_2CCH_3	180[c]	1	29	290,000
					21	96	960,000
4-bromoacetophenone	styrene	3(0.00001)	NaO_2CCH_3	180[c]	69	57.5[e]	5,750,000
bromobenzene	butylacrylate	3(0.2)	NaO_2CCH_3	140	18	51	255
4-bromoanisole	butylacrylate	3(0.2)	NaO_2CCH_3	140	10	6	30
4-bromoanisole	butylacrylate	3(0.2)	NaO_2CCH_3	180[c]	1	14	70
					19.5	75	375
4-bromoanisole	butylacrylate	3(0.2)	K_2CO_3	160	1	22	110
					18	88	440
4-bromoanisole	butylacrylate	3(0.01)[f]	K_2CO_3	160	1	23	2,300
					65	98	9,800
4-bromoacetophenone	butylacrylate	3(0.2)	NaO_2CCH_3	140[g]	2	32	160
4-bromoacetophenone	butylacrylate	5(0.2)	NaO_2CCH_3	140	1	53	265
					20	100	500
4-bromoacetophenone	butylacrylate	4(0.2)	NaO_2CCH_3	140	1	10	50
					13	100	500

[a]Reaction conditions: 50 mmol aryl bromide, 70 mmol alkene, 55 mmol base, 30 ml dimethylacetamide. [b]Determined by GC and/or ^1H NMR of reaction mixture samples, based on aryl bromide. [c]Refers to temperature of the heating bath, internal temperature range ~ 160-165 °C. [d]100 mmol. [e]Substantial polystyrene formation observed. [f]With 5 equivalents of tris(2,4-di-*tert*-butylphenyl)phosphite. [g]Under air

As with reactions catalysed by **1**,[5] the rate of coupling between arylbromides and butylacrylate catalysed by **3** was found to be dependent on the nature of the arylbromide - decreasing substantially with increasing electron density on the aryl ring. Slightly higher rates of activity and ultimate conversions were obtained with 4-bromoanisole as substrate when potassium carbonate was used as the base.

Substantial palladium deposition is seen in the coupling reactions of deactivated bromides at 0.2mol% catalyst concentration. This does not seem to be due to thermal decomposition as **3** shows good thermal stability in dimethylacetamide at 140°C even after 24 hours. Therefore it seems likely that the deposition is due to one or more catalyst deactivation pathways. We have previously demonstrated that addition of excess triarylphosphite to this catalyst system stabilises it against palladium deposition[4] and find here that a substantial increase in activity is observed in the 4-bromoanisole coupling reaction when excess ligand is added.

The high catalytic activity of **2** with its orthometallated aryl group and two phosphino residues[6] prompted us to investigate the use of the notionally similar **4**, the triphenylphosphine adduct of **3**, in the coupling of 4-bromoacetophenone with butylacrylate. However, this catalyst proved to be considerably less active than **3**. The metallated amine complex **5** proved to be at least as effective a catalyst as **3** at 0.2 mol% loading in the coupling of 4-bromoacetophenone with butylacrylate, despite the fact that quite considerable palladium deposition was observed. For this reason we have not currently studied the use of this catalyst further.

In summary, the extremely high catalytic activity and remarkable air and thermal stability of **3**, coupled with the very low cost of the commercially available ligand tris(2,4-di-*tert*-butylphenyl)phosphite - at least two orders of magnitude cheaper than the commonly used ligand tris(2-methylphenyl)phosphine - bodes well for its use not only in Heck reactions but also in other related C-C and C-X coupling processes, which we are currently investigating.

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Orthopalladated triaryl phosphite complexes as highly active catalysts in biaryl coupling reactions

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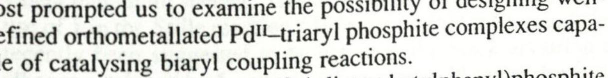
Orthopalladation of inexpensive, commercially available tris(2,4-di-*tert*-butylphenyl) phosphite gives a dimeric complex 3 which proves to be an extremely active catalyst in biaryl coupling reactions, giving unprecedented turnover numbers of up to 1 000 000 [mol product (mol Pd)$^{-1}$] and turnover frequencies of nearly 900 000 [mol product (mol Pd)$^{-1}$ h^{-1}] in the Suzuki reaction and turnover numbers of up to 830 000 in the Stille reaction.

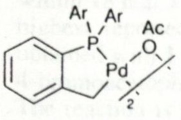
The use of triaryl phosphite complexes in catalysis has recently enjoyed a renaissance as a result of the activity they show in hydroformylation,[1] asymmetric hydrocyanation[2] and enantioselective alternating co-polymerisation of CO and propene.[3] Our interest lies in the synthesis and catalytic behaviour of orthometallated triaryl phosphite complexes and the role that the metallation plays in their activities.[4] So far the exploitation of such systems has been limited to a few catalytic reductions[4b,5] and only one example of catalytic C–C bond formation.[6]

One particularly important class of C–C coupling reaction is the catalytic formation of non-symmetric biaryls (Scheme 1) by the coupling of aryl halides with either arylboronic acids (the Suzuki reaction) or aryltin reagents (the Stille reaction). In general, catalyst loadings in such reactions are high (1–10 mol%) which imposes financial constraints on scaling up reactions and problems associated with catalyst removal. Therefore the synthesis of high activity catalysts which can be used in low concentrations is a desirable goal. Recently, Beller and co-workers reported the use of the metallated tris(2-methylphenyl)phosphinepalladium(II) complex **1** as an efficient catalyst for the Suzuki reaction.[7] The ready ability of triaryl phosphites to undergo analogous metallation reactions as well as their ease of synthesis, commercial availability and very low cost prompted us to examine the possibility of designing well-defined orthometallated Pd^{II}–triaryl phosphite complexes capable of catalysing biaryl coupling reactions.

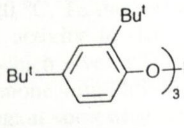


Scheme 1 Suzuki [E = B(OH)$_2$] and Stille (E = SnR$_3$) biaryl coupling reactions

The reaction of bulky tris(2,4-di-*tert*-butylphenyl)phosphite **2** with PdCl$_2$ gives the orthometallated dimer **3** in 96% yield. Compound **3** has been characterised by satisfactory elemental analysis, ^{1}H and ^{31}P NMR spectroscopy and by single crystal X-ray analysis (Fig. 1).§ Compound **3** shows remarkable stability to air and moisture—in solution it shows no sign of decomposition after several weeks, whilst solid samples can be kept in air for at least six months. No decomposition is observed when **3** is heated at 130 °C in toluene for 24 h, demonstrating that the catalyst also shows good thermal stability.



1 Ar = 2-MeC$_6$H$_4$



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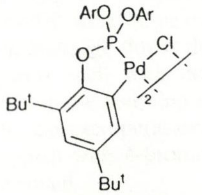

3 Ar = 2,4-Bu$^t_2$C$_6$H$_3$

The coupling of aryl halides and phenylboronic acid catalysed by **3** was investigated and representative results are summarised in Table 1. With 4-bromoacetophenone as substrate, extraordinarily high turnover numbers (TONs) of up to 1 000 000 [mol product (mol Pd)$^{-1}$] and turnover frequencies (TOFs) of nearly 900 000 [mol product (mol Pd)$^{-1}$ h^{-1}] were obtained at 110 °C. The previous highest activity with this substrate was achieved with complex **1** which gave a TON of 74 000 at the higher temperature of 130 °C over 16 h.[7] In the present reaction, lowering the temperature to 70 °C leads to a reduction in activity, but even at 20 °C high levels of activity are observed relative to previous reports of ambient temperature reactions.[8] The reaction is strongly influenced by a change of solvent or base, thus replacing toluene with THF at 70 °C leads to a substantial drop in rate. Similarly, with NaOAc as the base in DMA lower rates are observed.

With 4-bromobenzophenone as substrate high rates and ultimate conversions are also seen. As expected, activity decreases with increasing electron density on the aryl bromide. For instance, when 4-bromoanisole is employed TOFs are about two orders of magnitude lower than with 4-bromoacetophenone, however the ultimate TONs—up to 30 000—are, we believe, without precedent.

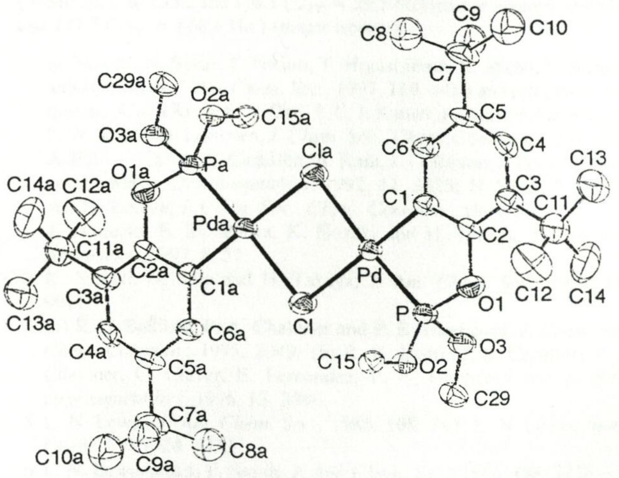

Fig. 1 Molecular structure of **3**. Thermal ellipsoids set at 50% probability. All H-atoms omitted for clarity, as are all but the *ipso*-carbons of the non-metallated aryl rings. Three Bu^t groups are disordered, only major orientation of C7–10 shown. Selected distances (Å) and angles (°): Pd–C(1) 1.998(6), Pd–Cl 2.4180(16), Pd–Cla 2.4073(17), Pd-P 2.1668(17), P–O1 1.592(4), P–O2 1.585(4), P–O3 1.584(4), C(1)–Pd–P 80.7(2), P–Pd–Cl ~~100.35~~(6), Cl–Pd–Cla 83.92(6), Cla–Pd–C1 ~~95.0~~(2), Pd–P–O1 ~~108.3~~(2), Pd–P–O2 120.4(2), Pd–P–O3 120.6(2).

Table 1 Suzuki coupling of aryl bromides with phenylboronic acid catalysed by **3**. Reaction conditions: 10 mmol aryl bromide, 15 mmol $PhB(OH)_2$, 20 mmol base in 30 ml solvent

Aryl bromide	Solvent	[Pd]/mol%	Base	T/°C	t/h	Conversion (%)[a]	TON/mol product (mol Pd)$^{-1}$
4-bromoacetophenone	DMA	0.1	NaOAc	130	18	66	660
4-bromoacetophenone	DMA	0.1	K_2CO_3	130	1	19	190
4-bromoacetophenone	DMA	0.1	K_2CO_3	130	15	98	980
4-bromoacetophenone	toluene	0.1	K_2CO_3	110	1	100	1000
4-bromoacetophenone	toluene	0.0001	K_2CO_3	110	1	87	870000
4-bromoacetophenone	toluene	0.0001	K_2CO_3	110	2.25	100	1000000
4-bromobenzophenone	toluene	0.0001	K_2CO_3	110	1	33	330000
4-bromobenzophenone	toluene	0.0001	K_2CO_3	110	15	60	600000
4-bromoacetophenone	toluene	0.1	K_2CO_3	70	2	100	1000
4-bromoacetophenone	THF	0.1	K_2CO_3	70	2	20	200
4-bromoacetophenone	toluene	0.1	K_2CO_3	20	2	95	950
4-bromoanisole	toluene	0.1	K_2CO_3	110	1	97.5	975
4-bromoanisole	toluene	0.001	K_2CO_3	110	1	5	5000
4-bromoanisole	toluene	0.001	K_2CO_3	110	15	16	16000
4-bromoanisole	toluene	0.001	K_2CO_3	130	15	30	30000

[a] Determined by GC and/or ^{1}H NMR analysis of reaction mixture samples, based on aryl bromide.

Table 2 Stille coupling of aryl bromides with $PhSnBu_3$ catalysed by **3**. Reaction conditions: 4 mmol aryl bromide, 5 mmol $PhSnBu_3$ in 20 ml toluene

Aryl bromide	[Pd]/mol%	T/°C	t/h	Conversion (%)[a]	TON/mol product (mol Pd)$^{-1}$
4-bromoacetophenone	0.2	100	17.5	54	270
4-bromoacetophenone	0.2	120	15	100	500
4-bromoacetophenone	0.0001	120	18	83	830000
4-bromoanisole	0.1	120	15	84	840

[a] Determined by GC and/or ^{1}H NMR analysis of reaction mixture samples, based on aryl halide.

In the coupling reactions with higher catalyst concentrations (≥0.1 mol% Pd) deposition of palladium is observed in the later stages of the reaction. Similarly, reaction of **3** with 1 equiv. of $PhB(OH)_2$ and K_2CO_3 in the absence of an aryl bromide leads to deposition. When this reaction was repeated with 1 equiv. of **2** included, decomposition was inhibited and it was possible to monitor the reaction by ^{31}P NMR spectroscopy. The spectrum after 30 min showed the mixture to be predominantly **2** and **3** but amongst other minor peaks two relatively major low field double doublets were apparent.¶ We have tentatively assigned these to the two isomers of $[Pd(Ph)\{P(OC_6H_2\text{-}2,4\text{-}Bu^t{}_2)(OC_6H_3\text{-}2,4\text{-}Bu^t{}_2)_2\}\{P(OC_6H_3\text{-}2,4\text{-}Bu^t{}_2)_3\}]$ in which the P atoms are disposed *trans* (major) or *cis* (minor). Also apparent is a small peak at δ −18.3. Such a high field shift is consistent with the formation of a Pd^0–phosphite complex. We postulate that reductive elimination of the orthometallated phosphite aryl and a phenyl groups occurs, yielding a catalytically active zero valent palladium species. This is in accord with findings for the use of **1** in the Stille reaction.[9] However, a Pd^{II}/Pd^{IV} couple has recently been suggested to be active in the Heck arylation of alkenes catalysed by **1** and related complexes[10] and at this stage we cannot rule out a related pathway.

Encouraged by the results obtained in the Suzuki reaction we decided to investigate the application of **3** to the Stille reaction. Representative results for the coupling of tributylphenyltin with aryl bromides are summarised in Table 2. With 4-bromoacetophenone as substrate TONs of up to 840000 were achieved within 18 h at 120 °C. To the best of our knowledge this is the highest reported activity to date, comparing well with that obtained with **1** which gives a TON of 1650 in the coupling of 4-bromoacetophenone with $PhSnMe_3$ at the same temperature.[9] The reaction is again somewhat more sluggish with 4-bromoanisole, but useful conversions are still obtained.

In summary the complex **3** is extremely active in biaryl coupling reactions under both Suzuki and Stille conditions and consequently can be used in very low concentrations. In view of this unprecedented activity and the low cost of **2**—at least two orders of magnitude cheaper than tris(2-methylphenyl)phosphine—we believe that it will be the catalyst of choice in such reactions. We are currently investigating its application to further catalytic processes. Preliminary investigations show it to be extremely active in the Heck arylation of alkenes, showing TONs of up to 5.75 million for activated aryl bromides, and these findings will be published elsewhere.

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Notes and References

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§ *Crystal data* for **3**: $C_{84}H_{124}Cl_2O_6P_2Pd_2$, M = 1575.47, triclinic, space group $P\bar{1}$, Z = 1, a = 11.957(1), b = 12.911(3), c = 15.300(3) Å, α = 81.08(2), β = 69.46(1), γ = 76.45(1)°, V = 2143.3(6) Å^3, T = 293(2) K, μ = 0.566 mm^{-1}, the final R-factor was 0.057 for 4257 reflections with $I > 2\sigma(I)$. CCDC 182/978.

¶ NMR data: δ_P 155.2 and 118.1 ($^2J_{PP}$ = 29.8 Hz) (minor isomer) and 141.4 and 117.3 ($^2J_{PP}$ = 868.4 Hz) (major isomer).

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Letter

Palladium bis(phosphinite) 'PCP'-pincer complexes and their application as catalysts in the Suzuki reaction

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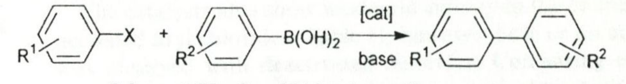
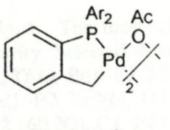
Palladium complexes of inexpensive, easily synthesised bis(phosphinite) 'PCP'-pincer ligands show good activity in the Suzuki coupling of deactivated and sterically hindered aryl bromides.

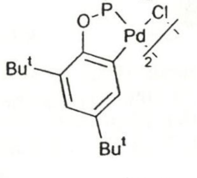
Palladium catalysed Suzuki coupling reactions (Scheme 1) generally require fairly high catalyst concentrations, limiting their attractiveness to large-scale commercial applications. This is due to technical problems and costs associated with removal of the spent palladium from the products. Consequently, there has recently been an interest in developing high-activity catalysts that can be used in very low concentrations. Beller and co-workers reported the use of the palladacyclic complex **1**,[1] formed by the metallation of tri(2-tolyl) phosphine, as an efficient catalyst for the Suzuki reaction.[2] We recently investigated the possibility of using related palladated triarylphosphite complexes and found that the complex **2** shows extremely high activity with both electronically activated and deactivated aryl bromides—considerably higher than the activity reported for **1**.[3]



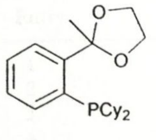
Scheme 1 The Suzuki biaryl coupling reaction



1: Ar = 2-MeC$_6$H$_4$



2: Ar = 2,4-Bu$^t_2$C$_6$H$_3$



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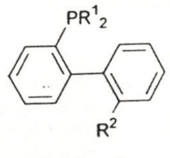
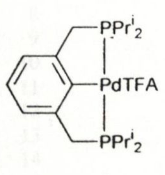
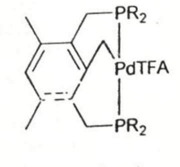


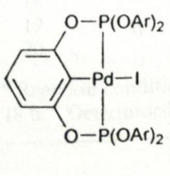
4: R^1 = Cy, Bu^t;
R^2 = H, Me, Pr^i, NMe$_2$



5a



5b: R = Pr^i, Bu^t



6: Ar = 4-MeOC$_6$H$_4$

Since then Fu and coworkers,[4] as well as Guram *et al.*,[5] have reported good, and Buchwald *et al.*[6] excellent, activity in the Suzuki reaction using palladium catalysts with the phosphine ligands PBu$^t_3$, **3** and **4**, respectively. However, the major drawbacks of these catalyst systems is that the phosphine ligands are comparatively difficult to make or are rather expensive—considerably more expensive than the palladium precursors.[7] We were therefore interested in continuing our studies on high activity catalysts derived from inexpensive, easily synthesised ligand sets. Inspired by the observations of Milstein *et al.*[8] and Shibasaki *et al.*[9] that palladated bis(phosphine) 'PCP'-complexes of type **5** and bis(phosphite) 'PCP'-complexes of type **6** show very high activity in the Heck reaction, we wished to see whether related bis(phosphinite) 'PCP'-pincer complexes would show high activity in the Suzuki reaction.

The ligands **7a** and **7b** are easily synthesised in good yields by the reaction of the appropriate aromatic diol with chlorodiphenylphosphine in toluene in the presence of triethylamine (Scheme 2). The reactions of these ligands with palladium trifluoroacetate in THF at room temperature gives the 'PCP'-pincer complexes **8a** and **8b** in good yields. The complexes show excellent air and moisture stability; for instance **8a** shows no sign of decomposition in aerobic solution in the presence of water after 10 days.

The crystal structure of one of the catalysts (**8a**) has been determined[10] and the molecular structure and relevant data are given in Fig. 1. The geometry of the palladium centre is distorted square planar and is grossly similar to that of the complex **6**.[9] The X-ray analysis confirms that palladation of the pincer ligand has occurred and that the two P-donor groups are in a distorted *trans* configuration. The trifluoroacetate ligand coordinates in a unidentate, non-symmetrical fashion, giving greater steric repulsion between the non-coordinated oxygen and the phenyl residues on P1 than those on P2. This is reflected in the considerably larger angle between O3–Pd1–P1 than between O3–Pd1–P2.

To the best of our knowledge no one has reported the application of palladium 'PCP'-pincer complexes as catalysts in the Suzuki reaction. Initially, the complexes were tested for activity in the coupling of phenylboronic acid with the 'easy-

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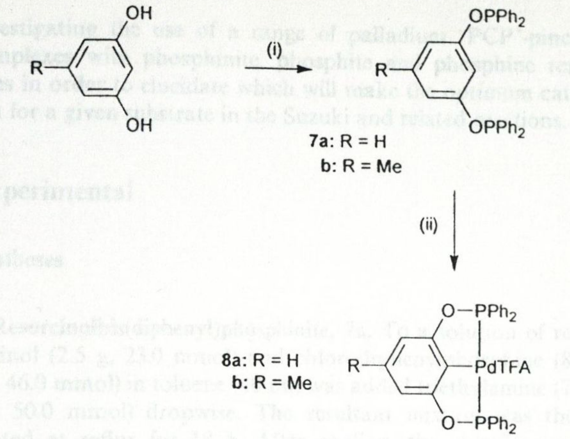

Scheme 2 (i) 2 $ClPPh_2$, 2.2 Et_3N, toluene, reflux. (ii) $Pd(TFA)_2$, THF.

to-couple' substrate 4-bromoacetophenone. The results were encouraging with the catalysts showing good activity at 130 °C (Table 1), although not as high as obtained previously with **2**.[3]

Next we examined the activity of the complexes with the electronically deactivated substrate 4-bromoanisole. In both cases good conversions were observed at one ten-thousandth catalyst concentration and very high turnover numbers (TONs) were observed at one hundred-thousandth catalyst concentration (Table 1). In contrast to the results obtained with 4-bromoacetophenone, catalyst **8a** shows >6 times higher activity with the more challenging substrate 4-bromoanisole than the previously reported catalyst **2** under identical conditions.[3] We believe this activity to be the highest yet reported for this substrate. Particularly interesting is the fact that catalysts **8a** and **8b** couple 4-bromoanisole with nearly the same activity as they show in the coupling of 4-bromoacetophenone. This may imply that the oxidative addition of the aryl bromide is not the rate-limiting step in the catalytic cycle. The catalysts show moderate to good activity at low concentrations in the coupling of the sterically hindered, electronically deactivated substrates 2-bromotoluene, 2-bromo-*p*-xylene and even 2-bromo-*m*-xylene. By comparison, palladium complexes of the ligands **4** and PBu^t_3 show TONs in the range 82–94 for these substrates, albeit run at lower temperatures.[4b,6]

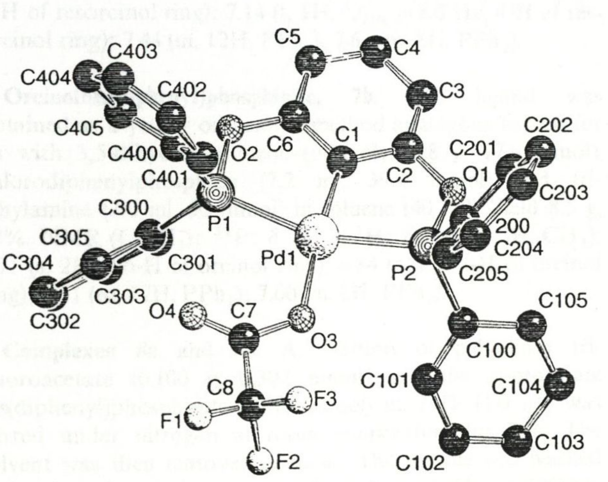

Fig. 1 The molecular structure of **8a**. All H atoms are omitted for clarity. Selected distances (Å) and angles (°): Pd1–C1 1.99(2), Pd1–P1 2.287(6), Pd1–P2 2.281(6), Pd1–O3 2.093(18); C1–Pd1–P1 81.5(6), C1–Pd1–P2 79.3(6), O3–Pd1–P1 104.8(5), O3–Pd1–P2 94.5(5), P1–Pd1–P2 160.2(2), C1–Pd1–O3 173.7(8).

The catalysts also show moderate activity in the coupling of activated aryl chlorides (Table 1); however, little or no activity was observed with deactivated chlorides. Comparing entries 14 and 17 to 20 it can be seen that the nature of the base plays a major role in the efficiency of coupling of the chlorides; this is an area we will investigate further. Particularly interesting was the fact that KF proved to be a very poor choice of base, even when the toluene was replaced with THF. This is in direct contrast with the finding by Buchwald *et al.* that this base–solvent mixture can give very high activity with palladium phosphine systems.[6]

Whilst it is difficult to establish any clear trends in catalyst activity on these preliminary data, on average **8b** shows slightly higher activity than **8a** in reactions at 0.01 to 0.001 mol% catalyst concentration, possibly due to the fact that **8b** has the more electron-rich Pd centre. At 0.0001 mol% catalyst concentration, **8a** seems more effective; this may be due to slightly higher stability and thus longevity of the catalyst.

In summary, we have demonstrated for the first time that palladium 'PCP'-pincer complexes can be used as high activity catalysts in the Suzuki reaction and that bis(phosphinite) 'PCP'-pincer complexes are ideal catalysts for the coupling of deactivated and sterically hindered aryl bromides as they are inexpensive and very easily synthesised. We are currently

Table 1 Suzuki coupling of aryl halides with phenylboronic acid catalysed by palladium 'PCP'-pincer complexes[a]

Entry	Aryl halide	Catalyst (mol%)	Base	Conv. (%)[b]	TON[c]
1	4-bromoacetophenone	**8a**(0.001)	K_2CO_3	59	59 000
2	4-bromoacetophenone	**8b**(0.001)	K_2CO_3	92	92 000
3	4-bromoacetophenone	**8a**(0.0001)	K_2CO_3	19	190 000
4	4-bromoacetophenone	**8b**(0.0001)	K_2CO_3	18	180 000
5	4-bromoanisole	**8a**(0.01)	K_2CO_3	61	6100
6	4-bromoanisole	**8b**(0.01)	K_2CO_3	72	7200
7	4-bromoanisole	**8a**(0.0001)	K_2CO_3	19	190 000
8	4-bromoanisole	**8b**(0.0001)	K_2CO_3	15	150 000
9	2-bromotoluene	**8a**(0.01)	K_2CO_3	87	8700
10	2-bromo-*p*-xylene	**8a**(0.01)	K_2CO_3	67	6700
11	2-bromo-*p*-xylene	**8b**(0.01)	K_2CO_3	63	6300
12	2-bromo-*m*-xylene	**8a**(0.01)	K_2CO_3	29	2900
13	2-bromo-*m*-xylene	**8b**(0.01)	K_2CO_3	30	3000
14	4-chloronitrobenzene	**8a**(0.01)	K_2CO_3	43	4300
15	4-chloronitrobenzene	**8b**(0.01)	K_2CO_3	40	4000
16	4-chloronitrobenzene	**8b**(0.1)	K_2CO_3	67	670
17	4-chloronitrobenzene	**8a**(0.01)	K_3PO_4	25	2500
18	4-chloronitrobenzene	**8a**(0.01)	$NaOBu^t$	0	0
19	4-chloronitrobenzene	**8a**(0.01)	KF	5	500
20	4-chloronitrobenzene	**8a**(0.01)	KF[d]	3	300

[a] Reaction conditions: 1.0 mmol aryl halide, 1.5 mmol $PhB(OH)_2$, 2.0 mmol base, 5 ml toluene, catalyst added in THF solution (0.1 ml), 130 °C, 18 h. [b] Determined by GC, based on aryl halide. [c] Defined as mol product per mol catalyst. [d] Solvent: 5 ml THF, 75 °C.

investigating the use of a range of palladium 'PCP'-pincer complexes with phosphinite, phosphite and phosphine residues in order to elucidate which will make the optimum catalyst for a given substrate in the Suzuki and related reactions.

Experimental

Syntheses

Resorcinolbis(diphenyl)phosphinite, 7a. To a solution of resorcinol (2.5 g, 23.0 mmol) and chlorodiphenylphosphine (8.4 ml, 46.0 mmol) in toluene (40 ml) was added triethylamine (7.0 ml, 50.0 mmol) dropwise. The resultant mixture was then heated at reflux for 18 h. After cooling, the volatiles were removed *in vacuo*, the residue was extracted with THF (20 ml) and the resultant solution was filtered through celite. The celite was washed with THF (2 × 20 ml), the extracts were combined and the solvent was removed *in vacuo* to yield the title product as a yellow–orange solid that was not purified further (8.2 g, 75%). NMR ($CDCl_3$): ^{31}P: δ 114.0; ^1H: δ 6.84 (d, 2H, $^3J_{HH} = 8.0$ Hz, 3,5-Hs of resorcinol ring); 7.02 (s, 1H, 1-H of resorcinol ring); 7.14 (t, 1H, $^3J_{HH} = 8.0$ Hz, 4-H of resorcinol ring); 7.44 (m, 12H, PPh_2); 7.63 (m, 8H, PPh_2).

Orcinolbis(diphenyl)phosphinite, 7b. The ligand was obtained as a yellow oil using a method analogous to that for **7a** with 3,5-dihydroxytoluene (orcinol; 2.18 g, 17.6 mmol), chlorodiphenylphosphine (7.2 ml, 39.4 mmol) and triethylamine (7.0 ml, 50 mmol) in toluene (40 ml). Yield 8.5 g, 98%. NMR ($CDCl_3$): ^{31}P: δ 111.3; ^1H: δ 2.29 (s, 3H, CH_3); 6.71 (s, 2H, 4,6-H of orcinol ring); 6.84 (s, 1H, 2-H of orcinol ring); 7.41 (m, 12H, PPh_2); 7.60 (m, 8H, PPh_2).

Complexes 8a and 8b. A solution of palladium trifluoroacetate (0.100 g, 0.302 mmol) and the appropriate bis(diphenyl)phosphinite (0.302 mmol) in THF (5.0 ml) was stirred under nitrogen at room temperature for 2 h. The solvent was then removed *in vacuo*. The residue was washed with ethanol and then recrystallised from dichloromethane–ethanol. Complex **8a** was obtained as a colourless solid (0.175 g, 85%). Crystals suitable for single crystal X-ray analysis were obtained by layering a solution of **8a** in dichloromethane with hexane. Anal. calc. for $C_{32}H_{23}F_3O_4P_2Pd$: C 55.15; H 3.3. Found: C 54.85; H 3.55%. NMR ($CDCl_3$): ^{31}P: δ 146.2; ^1H: δ 6.74 (d, 2H, $^2J_{HH} = 8.0$ Hz, 3,5-Hs of resorcinol ring); 7.12 (t, 1H, $^3J_{HH} = 8.0$ Hz, 4-H of resorcinol ring); 7.57 (m, 12H, PPh_2); 7.90 (m, 8H, PPh_2).

Complex **8b** was obtained as a colourless solid (0.166 g, 78%). Anal. calc. for $C_{33}H_{25}F_3O_4P_2Pd$: C 55.75; H 3.5. Found: C 55.1; H 3.3% NMR ($CDCl_3$): ^{31}P: δ 145.6; ^1H: δ 2.28 (s, 3H, CH_3); 6.57 (s, 2H, 4,6-Hs of orcinol ring); 7.49 (m, 12H, PPh_2); 7.86 (m, 8H, PPh_2).

Acknowledgements

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Appendix 2

X-ray data for complex 37a

```
For NJC letter article entitled 'palladium bisphosphite and bis ph
osphinite PCP pincer complexes
Authors: Bedford, Draper, Scully

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_cell_length_c                    17.2811(14)
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_cell_angle_beta                  90.00
_cell_angle_gamma                 90.00
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_cell_measurement_temperature     293(2)

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_computing_molecular_graphics      schakal

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 based
 on F, with F set to zero for negative F^2^. The threshold express
ion of
 F^2^ > 2sigma(F^2^) is used only for calculating R-factors(gt) et
c. and is
 not relevant to the choice of reflections for refinement.  R-fact
ors based
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on F^2^are statistically about twice as large as those based on
F, and R-
factors based on ALL data will be even larger.
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^2^)/3'
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O3 O 1.0182(19) -0.0552(12) -0.0725(9) 0.059(5) Uani 1 1 d . . .
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H103 H 0.5402 -0.3193 -0.0744 0.070 Uiso 1 1 calc R . .
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C2 0.046(8) 0.022(10) 0.023(8) 0.009(7) 0.011(8) 0.002(8)
C3 0.054(11) 0.036(12) 0.035(10) 0.000(8) 0.004(8) 0.001(10)
C4 0.063(10) 0.044(13) 0.032(10) -0.005(9) 0.005(10) 0.004(12)
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C7 0.042(7) 0.039(7) 0.037(7) -0.001(5) 0.003(5) 0.003(5)
C8 0.09(2) 0.12(3) 0.041(15) -0.013(17) 0.026(17) 0.04(2)
C100 0.065(11) 0.025(8) 0.027(10) 0.005(8) -0.020(10) -0.019(8)
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C102 0.070(11) 0.029(9) 0.09(2) 0.000(13) 0.013(17) -0.012(10)
C103 0.078(13) 0.033(9) 0.063(15) 0.012(11) -0.006(15) -0.025(9)
C104 0.062(13) 0.054(11) 0.066(16) 0.013(13) -0.047(14) -0.020(8)
C105 0.062(10) 0.041(9) 0.048(13) -0.002(10) 0.012(12) -0.012(9)
C200 0.038(6) 0.033(6) 0.035(6) -0.003(5) -0.002(5) 0.000(5)
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C205 0.072(18) 0.045(15) 0.045(13) -0.012(11) 0.000(13) 0.011(13)
C300 0.073(12) 0.023(11) 0.040(11) 0.009(8) -0.001(10) 0.001(9)
C301 0.072(16) 0.062(18) 0.073(18) 0.030(14) 0.002(13) -0.018(13)
C302 0.102(19) 0.07(2) 0.10(2) 0.043(18) -0.026(18) 0.000(19)
C303 0.13(2) 0.08(2) 0.09(2) 0.06(2) 0.004(18) 0.00(2)
C304 0.072(15) 0.050(15) 0.074(16) 0.007(12) -0.020(12) 0.003(13)
C305 0.052(11) 0.039(12) 0.044(12) 0.001(9) -0.019(8) -0.009(10)
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C402 0.13(3) 0.030(13) 0.042(14) 0.018(11) 0.023(17) 0.012(15)
C403 0.074(17) 0.029(12) 0.056(16) 0.005(11) 0.012(14) -0.008(11)
C404 0.10(2) 0.030(12) 0.055(15) -0.007(11) -0.020(16) -0.005(14)
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angles
 and torsion angles; correlations between esds in cell parameters
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Pd1 P2 2.281(6) . ?
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P1 O2 1.638(16) . ?
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P1 C400 1.863(11) . ?
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O2 C6 1.38(3) . ?
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O4 C7 1.16(3) . ?
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O3 Pd1 P1 104.8(5) . . ?
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O1 P2 C200 103.8(7) . . ?
C100 P2 C200 107.5(7) . . ?
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C2 C1 Pd1 122.8(15) . . ?
C6 C1 Pd1 119.3(16) . . ?
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C3 C2 C1 121(2) . . ?
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O2 C6 C5 119.9(19) . . ?
O2 C6 C1 119.3(19) . . ?
C5 C6 C1 121(2) . . ?
O4 C7 O3 129(2) . . ?
O4 C7 C8 122(2) . . ?
O3 C7 C8 108(2) . . ?
F1 C8 F3 105(3) . . ?
F1 C8 F2 108(3) . . ?
F3 C8 F2 109(4) . . ?
F1 C8 C7 111(3) . . ?
F3 C8 C7 112(3) . . ?
F2 C8 C7 111(3) . . ?
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C302 C303 C301 119(3) . . ?
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C300 C305 C304 116.7(17) . . ?
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C405 C400 P1 118.5(4) . . ?
C401 C400 P1 115.7(3) . . ?
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Appendix 3

X-ray data for complex 42

Table 1. Crystal data and structure refinement.

Identification code	**00SRC168**	
Empirical formula	$C_{35}H_{24}F_6O_6P_2Pd_2 \cdot CHCl_3$	
Formula weight	1048.65	
Temperature	296(2) K	
Wavelength	0.71073 Å	
Crystal system	Monoclinic	
Space group	*C*2/*c*	
Unit cell dimensions	$a = 33.6248(3)$ Å	
	$b = 14.1187(2)$ Å	$\beta = 124.2266(9)°$
	$c = 20.2972(2)$ Å	
Volume	7967.12(15) Å^3	
Z	8	
Density (calculated)	1.749 Mg / m^3	
Absorption coefficient	1.256 mm^{-1}	
F(000)	4128	
Crystal	Yellow Block	
Crystal size	$0.10 \times 0.10 \times 0.08$ mm^3	
θ range for data collection	2.93 – 25.03°	
Index ranges	$-39 \le h \le 40, -15 \le k \le 16, -23 \le l \le 24$	
Reflections collected	32009	
Independent reflections	7035 [$R_{int} = 0.0508$]	
Completeness to $\theta = 25.03°$	99.8 %	
Max. and min. transmission	0.9117 and 0.8847	
Refinement method	Full-matrix least-squares on F^2	
Data / restraints / parameters	7035 / 9 / 437	
Goodness-of-fit on F^2	1.036	
Final *R* indices [$F^2 > 2\sigma(F^2)$]	$R1 = 0.0472$, $wR2 = 0.1294$	
R indices (all data)	$R1 = 0.0640$, $wR2 = 0.1426$	
Largest diff. peak and hole	0.914 and –0.805 e Å^{-3}	

Diffractometer: *Enraf Nonius KappaCCD* area detector (ϕ scans and ω scans to fill *Ewald* sphere). **Data collection and cell refinement**: *Denzo* (Z. Otwinowski & W. Minor, *Methods in Enzymology* (1997) Vol. **276**: *Macromolecular Crystallography*, part A, pp. 307–326; C. W. Carter, Jr. & R. M. Sweet, Eds., Academic Press). **Absorption correction**: *SORTAV* (R. H. Blessing, Acta Cryst. **A51** (1995) 33–37; R. H. Blessing, J. Appl. Cryst. **30** (1997) 421–426). **Program used to solve structure**: *SHELXS97* (G. M. Sheldrick, Acta Cryst. (1990) **A46** 467–473). **Program used to refine structure**: *SHELXL97* (G. M. Sheldrick (1997), University of Göttingen, Germany).

Further information: http://www.soton.ac.uk/~xservice/strat.htm

Special details: All hydrogen atoms were placed in idealised positions and refined using a riding model. C-F and C-Cl distances were restrained to standard values and the geometry of the phenyl rings were also restrained.

C12–C7–P1	119.8(2)
C9–C8–C7	120.0
C8–C9–C10	120.0
C9–C10–C11	120.0
C12–C11–C10	120.0
C11–C12–C7	120.0
C14–C13–C18	120.0
C14–C13–P2	120.5(2)
C18–C13–P2	119.4(2)
C15–C14–C13	120.0
C14–C15–C16	120.0
C17–C16–C15	120.0
C16–C17–C18	120.0
C17–C18–C13	120.0
C20–C19–C24	120.0
C20–C19–P2	119.2(3)
C24–C19–P2	120.8(3)
C21–C20–C19	120.0
C22–C21–C20	120.0
C21–C22–C23	120.0
C24–C23–C22	120.0
C23–C24–C19	120.0
O2–C25–O1	129.7(5)
O2–C25–C26	116.5(4)
O1–C25–C26	113.8(4)
F2–C26–F3	103.2(5)
F2–C26–F1	102.4(5)
F3–C26–F1	102.1(5)
F2–C26–C25	114.1(4)
F3–C26–C25	116.7(4)
F1–C26–C25	116.3(4)
O3–C27–O4	131.4(5)
O3–C27–C28	114.9(4)
O4–C27–C28	113.4(4)
F5–C28–F4	102.5(5)
F5–C28–F6	104.1(5)
F4–C28–F6	106.8(6)
F5–C28–C27	114.4(4)
F4–C28–C27	113.2(4)
F6–C28–C27	114.7(4)
C30–C29–C34	120.0
C30–C29–Pd2	118.46(15)
C34–C29–Pd2	121.37(15)
O6–C30–C29	120.8(2)
O6–C30–C31	119.2(2)
C29–C30–C31	120.0
C30–C31–C32	120.0
C30–C31–C35	120.2(3)
C32–C31–C35	119.7(3)
O5–C32–C31	120.5(2)
O5–C32–C33	119.1(2)
C31–C32–C33	120.0
C34–C33–C32	120.0
C34–C33–Pd1^{i}	122.47(15)
C32–C33–Pd1^{i}	117.53(15)
C33–C34–C29	120.0
Cl3–C36–Cl2	106.5(5)
Cl3–C36–Cl1	104.3(4)
Cl2–C36–Cl1	102.7(4)
C25–O1–Pd1	128.0(3)
C25–O2–Pd2	123.5(3)
C27–O3–Pd1	126.6(3)
C27–O4–Pd2	123.3(3)
C32–O5–P1^{i}	107.7(2)
C30–O6–P2	111.5(2)
O5^{i}–P1–C1	103.02(17)
O5^{i}–P1–C7	103.7(2)
C1–P1–C7	105.79(19)
O5^{i}–P1–Pd1	105.26(14)
C1–P1–Pd1	119.02(15)
C7–P1–Pd1	117.93(13)
O6–P2–C19	102.7(2)
O6–P2–C13	104.98(19)
C19–P2–C13	105.6(2)
O6–P2–Pd2	108.90(13)
C19–P2–Pd2	120.43(16)
C13–P2–Pd2	112.82(16)

Symmetry transformations used to generate equivalent atoms:
(i) –x,y,–z+1/2

Table 3. Bond lengths [Å] and angles [°].

Pd1–C33^{i}	2.007(8)	C20–C21	1.3900
Pd1–O1	2.127(4)	C21–C22	1.3900
Pd1–O3	2.151(4)	C22–C23	1.3900
Pd1–P1	2.1749(14)	C23–C24	1.3900
Pd2–C29	2.0015(19)	C25–O2	1.226(6)
Pd2–O2	2.142(4)	C25–O1	1.245(6)
Pd2–O4	2.157(3)	C25–C26	1.440(7)
Pd2–P2	2.1681(14)	C26–F2	1.372(2)
C1–C2	1.3900	C26–F3	1.372(2)
C1–C6	1.3900	C26–F1	1.373(2)
C1–P1	1.774(3)	C27–O3	1.229(6)
C2–C3	1.3900	C27–O4	1.244(6)
C3–C4	1.3900	C27–C28	1.480(7)
C4–C5	1.3900	C28–F5	1.373(2)
C5–C6	1.3900	C28–F4	1.373(2)
C7–C8	1.3900	C28–F6	1.374(2)
C7–C12	1.3900	C29–C30	1.3900
C7–P1	1.791(3)	C29–C34	1.3900
C8–C9	1.3900	C30–O6	1.366(4)
C9–C10	1.3900	C30–C31	1.3900
C10–C11	1.3900	C31–C32	1.3900
C11–C12	1.3900	C31–C35	1.546(5)
C13–C14	1.3900	C32–O5	1.363(4)
C13–C18	1.3900	C32–C33	1.3900
C13–P2	1.797(3)	C33–C34	1.3900
C14–C15	1.3900	C33–Pd1^{i}	2.007(2)
C15–C16	1.3900	Cl1–C36	1.768(2)
C16–C17	1.3900	Cl2–C36	1.767(2)
C17–C18	1.3900	Cl3–C36	1.767(2)
C19–C20	1.3900	O5–P1^{i}	1.631(3)
C19–C24	1.3900	O6–P2	1.622(3)
C19–P2	1.785(3)	P1–O5^{i}	1.631(3)

C33^{i}–Pd1–O1	94.9(3)	O4–Pd2–P2	96.28(11)
C33^{i}–Pd1–O3	175.78(13)	C2–C1–C6	120.0
O1–Pd1–O3	86.75(15)	C2–C1–P1	122.7(2)
C33^{i}–Pd1–P1	77.0(3)	C6–C1–P1	117.3(2)
O1–Pd1–P1	165.28(10)	C3–C2–C1	120.0
O3–Pd1–P1	100.62(11)	C4–C3–C2	120.0
C29–Pd2–O2	96.63(12)	C3–C4–C5	120.0
C29–Pd2–O4	176.54(13)	C6–C5–C4	120.0
O2–Pd2–O4	86.75(15)	C5–C6–C1	120.0
C29–Pd2–P2	80.26(9)	C8–C7–C12	120.0
O2–Pd2–P2	165.98(10)	C8–C7–P1	119.9(2)

Appendix 4

X-ray data for complex 57

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 'x-1/2, -y-1/2, z'

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_computing_molecular_graphics     ?
_computing_publication_material   ?

_refine_special_details
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 F^2^ > 2sigma(F^2^) is used only for calculating R-factors(gt) etc. and is
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 factors based on ALL data will be even larger.
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Cl1 Cl 0.5643(3) 0.2976(3) 0.7490(3) 0.0700(15) Uani 1 1 d . . .
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Cl3 Cl 0.3588(4) 0.5013(4) 0.5954(3) 0.0878(18) Uani 1 1 d . . .
O3 O 0.6592(7) 0.5015(7) 0.7843(6) 0.049(3) Uani 1 1 d . . .
O1 O 0.5167(8) 0.5978(8) 0.7349(6) 0.054(3) Uani 1 1 d . . .
O2 O 0.5453(8) 0.4868(7) 0.8383(6) 0.047(3) Uani 1 1 d . . .
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C2 C 0.8087(12) 0.4492(13) 0.7939(10) 0.056(5) Uani 1 1 d . . .
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H3 H 0.9298 0.4137 0.7832 0.085 Uiso 1 1 calc R . .
C4 C 0.8491(13) 0.4604(12) 0.6804(11) 0.059(5) Uani 1 1 d . . .
C5 C 0.7609(14) 0.4985(12) 0.6387(12) 0.072(6) Uani 1 1 d . . .
H5 H 0.7452 0.5143 0.5872 0.086 Uiso 1 1 calc R . .
C6 C 0.6957(12) 0.5134(12) 0.6724(9) 0.045(5) Uani 1 1 d . . .
C7 C 0.6057(12) 0.5588(12) 0.6266(9) 0.049(5) Uani 1 1 d . . .
H7A H 0.5530 0.5233 0.6255 0.059 Uiso 1 1 calc R . .
H7B H 0.6001 0.5665 0.5736 0.059 Uiso 1 1 calc R . .
C8 C 0.6024(12) 0.6466(13) 0.6616(8) 0.050(5) Uani 1 1 d . . .
C9 C 0.5625(12) 0.6665(14) 0.7121(9) 0.051(5) Uani 1 1 d . . .
```

```
C10 C 0.5611(11) 0.7474(13) 0.7451(9) 0.050(5) Uani 1 1 d . . .
C11 C 0.6023(12) 0.8147(14) 0.7149(11) 0.064(6) Uani 1 1 d . . .
H11 H 0.6036 0.8713 0.7339 0.077 Uiso 1 1 calc R . .
C12 C 0.6397(12) 0.8026(15) 0.6605(12) 0.067(6) Uani 1 1 d . . .
C13 C 0.6364(12) 0.7184(13) 0.6320(11) 0.058(5) Uani 1 1 d . . .
H13 H 0.6571 0.7087 0.5923 0.070 Uiso 1 1 calc R . .
C14 C 0.4617(13) 0.4684(11) 0.8502(9) 0.044(4) Uani 1 1 d . . .
C15 C 0.3803(16) 0.5040(13) 0.8089(12) 0.071(6) Uani 1 1 d . . .
H15 H 0.3755 0.5421 0.7688 0.085 Uiso 1 1 calc R . .
C16 C 0.2994(15) 0.4857(14) 0.8243(12) 0.078(7) Uani 1 1 d . . .
H16 H 0.2405 0.5086 0.7938 0.094 Uiso 1 1 calc R . .
C17 C 0.3116(17) 0.4331(14) 0.8857(12) 0.085(7) Uani 1 1 d . . .
C18 C 0.3964(17) 0.3960(15) 0.9276(12) 0.090(7) Uani 1 1 d . . .
H18 H 0.4020 0.3589 0.9686 0.108 Uiso 1 1 calc R . .
C19 C 0.4763(16) 0.4123(14) 0.9105(13) 0.065(6) Uani 1 1 d . . .
C20 C 0.5705(18) 0.3712(18) 0.9653(13) 0.128(10) Uani 1 1 d . . .
H20A H 0.5594 0.3338 1.0020 0.192 Uiso 1 1 calc R . .
H20B H 0.6138 0.4168 0.9924 0.192 Uiso 1 1 calc R . .
H20C H 0.5968 0.3373 0.9355 0.192 Uiso 1 1 calc R . .
C21 C 0.2216(17) 0.4131(18) 0.9029(17) 0.148(12) Uani 1 1 d . . .
H21A H 0.1685 0.4445 0.8668 0.221 Uiso 1 1 calc R . .
H21B H 0.2326 0.4313 0.9547 0.221 Uiso 1 1 calc R . .
H21C H 0.2088 0.3513 0.8978 0.221 Uiso 1 1 calc R . .
C22 C 0.8420(13) 0.4301(16) 0.8777(10) 0.074(7) Uani 1 1 d . . .
C23 C 0.8446(16) 0.5142(17) 0.9215(13) 0.108(9) Uani 1 1 d . . .
H23A H 0.8651 0.5017 0.9758 0.162 Uiso 1 1 calc R . .
H23B H 0.7827 0.5397 0.9028 0.162 Uiso 1 1 calc R . .
H23C H 0.8878 0.5547 0.9137 0.162 Uiso 1 1 calc R . .
C24 C 0.7791(13) 0.3667(14) 0.8969(10) 0.080(7) Uani 1 1 d . . .
H24A H 0.8038 0.3572 0.9519 0.119 Uiso 1 1 calc R . .
H24B H 0.7769 0.3120 0.8710 0.119 Uiso 1 1 calc R . .
H24C H 0.7166 0.3906 0.8801 0.119 Uiso 1 1 calc R . .
C25 C 0.9415(13) 0.3933(18) 0.9139(14) 0.112(9) Uani 1 1 d . . .
H25A H 0.9574 0.3817 0.9679 0.168 Uiso 1 1 calc R . .
H25B H 0.9851 0.4352 0.9086 0.168 Uiso 1 1 calc R . .
H25C H 0.9449 0.3399 0.8881 0.168 Uiso 1 1 calc R . .
C26 C 0.9167(14) 0.4442(15) 0.6408(12) 0.099(7) Uani 1 1 d . . .
H26A H 0.8895 0.4662 0.5887 0.149 Uiso 1 1 calc R . .
H26B H 0.9280 0.3824 0.6398 0.149 Uiso 1 1 calc R . .
H26C H 0.9753 0.4737 0.6688 0.149 Uiso 1 1 calc R . .
C27 C 0.6760(15) 0.8789(13) 0.6269(14) 0.096(8) Uani 1 1 d . . .
H27A H 0.6993 0.8569 0.5899 0.144 Uiso 1 1 calc R . .
H27B H 0.7260 0.9083 0.6680 0.144 Uiso 1 1 calc R . .
H27C H 0.6254 0.9194 0.6019 0.144 Uiso 1 1 calc R . .
C28 C 0.5219(19) 0.7697(13) 0.8037(12) 0.077(7) Uani 1 1 d . . .
C29 C 0.5385(19) 0.8641(14) 0.8305(13) 0.113(9) Uani 1 1 d . . .
H29A H 0.5046 0.9022 0.7879 0.169 Uiso 1 1 calc R . .
H29B H 0.6047 0.8769 0.8492 0.169 Uiso 1 1 calc R . .
H29C H 0.5168 0.8729 0.8714 0.169 Uiso 1 1 calc R . .
C30 C 0.4138(17) 0.7536(17) 0.7701(16) 0.118(11) Uani 1 1 d . . .
H30A H 0.3837 0.7910 0.7260 0.178 Uiso 1 1 calc R . .
H30B H 0.3897 0.7665 0.8090 0.178 Uiso 1 1 calc R . .
H30C H 0.4011 0.6935 0.7545 0.178 Uiso 1 1 calc R . .
C31 C 0.5709(19) 0.7161(14) 0.8735(13) 0.117(10) Uani 1 1 d . . .
H31A H 0.5604 0.6551 0.8604 0.175 Uiso 1 1 calc R . .
H31B H 0.5469 0.7301 0.9122 0.175 Uiso 1 1 calc R . .
H31C H 0.6374 0.7282 0.8934 0.175 Uiso 1 1 calc R . .
N1 N 0.1941(10) 0.2956(12) 0.5758(10) 0.079(5) Uani 1 1 d . . .
H1 H 0.2540 0.2970 0.5775 0.095 Uiso 1 1 calc R . .
C100 C 0.1415(19) 0.364(2) 0.508(3) 0.24(3) Uani 1 1 d . . .
H10A H 0.1797 0.4156 0.5118 0.292 Uiso 1 1 calc R . .
```

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H10B H 0.1251 0.3374 0.4571 0.292 Uiso 1 1 calc R . .
C101 C 0.210(3) 0.323(3) 0.660(2) 0.20(2) Uani 1 1 d . . .
H10C H 0.2229 0.3856 0.6645 0.245 Uiso 1 1 calc R . .
H10D H 0.1514 0.3142 0.6661 0.245 Uiso 1 1 calc R . .
C102 C 0.162(2) 0.212(2) 0.541(3) 0.23(3) Uani 1 1 d . . .
H10E H 0.2191 0.1857 0.5406 0.277 Uiso 1 1 calc R . .
H10F H 0.1493 0.1809 0.5807 0.277 Uiso 1 1 calc R . .
C103 C 0.059(3) 0.384(3) 0.522(2) 0.22(2) Uani 1 1 d . . .
H10G H 0.0194 0.4229 0.4828 0.328 Uiso 1 1 calc R . .
H10H H 0.0778 0.4116 0.5720 0.328 Uiso 1 1 calc R . .
H10I H 0.0256 0.3309 0.5217 0.328 Uiso 1 1 calc R . .
C104 C 0.282(2) 0.2823(18) 0.7237(15) 0.128(11) Uani 1 1 d . . .
H10J H 0.2829 0.3067 0.7711 0.192 Uiso 1 1 calc R . .
H10K H 0.3421 0.2920 0.7207 0.192 Uiso 1 1 calc R . .
H10L H 0.2700 0.2205 0.7225 0.192 Uiso 1 1 calc R . .
C105 C 0.116(3) 0.192(4) 0.496(4) 0.53(9) Uani 1 1 d . . .
H10M H 0.1083 0.1296 0.5001 0.796 Uiso 1 1 calc R . .
H10N H 0.1341 0.2028 0.4531 0.796 Uiso 1 1 calc R . .
H10O H 0.0574 0.2207 0.4868 0.796 Uiso 1 1 calc R . .

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 _atom_site_aniso_U_23
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Pd1 0.0379(7) 0.0593(10) 0.0490(8) -0.0011(9) 0.0202(6) -0.0045(9)
P1 0.058(3) 0.043(3) 0.046(3) 0.006(2) 0.028(3) -0.004(3)
Cl1 0.064(3) 0.056(4) 0.069(4) 0.001(3) 0.004(3) 0.006(3)
Cl2 0.060(3) 0.104(5) 0.073(4) -0.027(3) 0.025(3) -0.024(3)
Cl3 0.068(4) 0.109(5) 0.076(4) 0.025(4) 0.018(3) 0.020(3)
O3 0.046(7) 0.054(8) 0.052(8) 0.003(6) 0.024(6) -0.002(6)
O1 0.074(8) 0.046(8) 0.060(7) 0.020(7) 0.048(7) -0.001(8)
O2 0.049(8) 0.070(8) 0.018(6) 0.000(6) 0.010(6) 0.003(7)
C1 0.066(14) 0.045(11) 0.078(14) -0.006(10) 0.046(12) -0.013(10)
C2 0.031(10) 0.078(14) 0.036(12) -0.016(10) -0.010(10) -0.025(10)
C3 0.047(12) 0.074(16) 0.081(15) -0.018(12) 0.014(12) -0.026(11)
C4 0.057(13) 0.072(14) 0.059(13) -0.010(11) 0.035(12) -0.004(11)
C5 0.075(14) 0.053(13) 0.102(16) -0.002(12) 0.051(14) -0.018(11)
C6 0.052(12) 0.048(13) 0.043(10) -0.011(10) 0.029(10) -0.018(10)
C7 0.044(11) 0.064(14) 0.037(10) 0.015(10) 0.012(9) -0.001(10)
C8 0.056(12) 0.057(13) 0.029(8) 0.010(9) 0.009(9) -0.002(10)
C9 0.056(12) 0.072(16) 0.023(10) 0.010(10) 0.014(10) 0.010(11)
C10 0.039(11) 0.061(14) 0.044(10) -0.005(10) 0.010(9) -0.007(10)
C11 0.049(11) 0.075(16) 0.056(14) 0.008(13) 0.008(11) -0.010(11)
C12 0.054(11) 0.066(17) 0.085(15) 0.033(13) 0.032(11) 0.007(11)
C13 0.045(12) 0.080(15) 0.060(14) 0.025(12) 0.031(11) 0.008(10)
C14 0.062(13) 0.040(11) 0.030(9) 0.007(8) 0.019(9) -0.002(10)
C15 0.103(17) 0.071(16) 0.063(16) 0.031(13) 0.057(15) 0.022(14)
C16 0.077(16) 0.080(18) 0.091(16) 0.028(14) 0.048(14) 0.032(13)
C17 0.119(19) 0.099(17) 0.060(15) 0.019(13) 0.062(15) -0.005(14)
C18 0.116(18) 0.089(18) 0.084(14) 0.050(15) 0.060(14) 0.020(17)
C19 0.096(16) 0.059(15) 0.066(16) -0.006(14) 0.058(14) -0.001(13)
C20 0.13(2) 0.14(3) 0.138(19) 0.062(18) 0.080(18) 0.01(2)
C21 0.14(2) 0.15(2) 0.24(3) 0.01(2) 0.17(3) -0.01(2)
C22 0.044(12) 0.12(2) 0.051(12) -0.011(13) 0.010(10) -0.023(13)
C23 0.085(18) 0.14(3) 0.074(18) -0.041(18) 0.008(15) -0.038(17)
C24 0.074(14) 0.11(2) 0.041(12) 0.006(12) 0.009(11) -0.001(14)
C25 0.047(13) 0.14(2) 0.12(2) 0.04(2) 0.007(14) 0.010(16)
```

```
C26 0.084(15) 0.119(19) 0.125(18) 0.001(16) 0.074(15) -0.005(14)
C27 0.091(16) 0.068(18) 0.15(2) -0.002(15) 0.069(16) -0.036(13)
C28 0.15(2) 0.044(14) 0.053(15) 0.014(11) 0.053(17) 0.017(13)
C29 0.19(3) 0.087(18) 0.091(16) 0.001(15) 0.083(18) 0.022(18)
C30 0.10(2) 0.09(2) 0.19(3) 0.00(2) 0.09(2) 0.021(17)
C31 0.22(3) 0.049(15) 0.12(2) -0.009(15) 0.10(2) 0.001(17)
N1 0.032(9) 0.097(15) 0.103(14) 0.000(12) 0.021(9) -0.023(9)
C100 0.061(18) 0.15(3) 0.51(8) 0.20(4) 0.10(3) 0.042(19)
C101 0.17(4) 0.34(6) 0.17(3) 0.03(4) 0.14(3) 0.08(4)
C102 0.09(2) 0.08(3) 0.43(8) 0.04(4) 0.00(3) -0.06(2)
C103 0.23(4) 0.22(5) 0.16(4) 0.01(4) 0.02(3) -0.05(4)
C104 0.14(3) 0.14(2) 0.10(2) 0.03(2) 0.05(2) 0.00(2)
C105 0.14(4) 0.49(12) 0.63(12) -0.48(11) -0.20(5) 0.11(5)

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;
 All esds (except the esd in the dihedral angle between two l.s. planes)
 are estimated using the full covariance matrix.  The cell esds are taken
 into account individually in the estimation of esds in distances, angles
 and torsion angles; correlations between esds in cell parameters are only
 used when they are defined by crystal symmetry.  An approximate (isotropic)
 treatment of cell esds is used for estimating esds involving l.s. planes.
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Pd1 Cl1 2.266(5) . ?
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P1 O1 1.593(13) . ?
P1 O2 1.582(11) . ?
P1 O3 1.581(11) . ?
O3 C1 1.416(18) . ?
O1 C9 1.42(2) . ?
O2 C14 1.420(19) . ?
C1 C6 1.36(2) . ?
C1 C2 1.41(2) . ?
C2 C3 1.42(2) . ?
C2 C22 1.48(2) . ?
C3 C4 1.36(2) . ?
C4 C5 1.40(2) . ?
C4 C26 1.52(2) . ?
C5 C6 1.40(2) . ?
C6 C7 1.49(2) . ?
C7 C8 1.50(2) . ?
C8 C9 1.35(2) . ?
C8 C13 1.42(2) . ?
C9 C10 1.38(2) . ?
C10 C11 1.44(2) . ?
C10 C28 1.49(2) . ?
C11 C12 1.37(2) . ?
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C12 C27 1.53(2) . ?
C14 C15 1.30(2) . ?
C14 C19 1.37(2) . ?
C15 C16 1.41(3) . ?
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C16 C17 1.35(3) . ?
C17 C18 1.35(3) . ?
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C18 C19 1.41(3) . ?
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C22 C23 1.52(3) . ?
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C22 C24 1.51(3) . ?
C28 C31 1.48(3) . ?
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C28 C30 1.55(3) . ?
N1 C102 1.43(4) . ?
N1 C101 1.56(3) . ?
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Cl1 Pd1 Cl3 174.3(2) . . ?
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Cl1 Pd1 Cl2 90.8(2) . . ?
Cl3 Pd1 Cl2 89.5(2) . . ?
O1 P1 O2 102.7(6) . . ?
O1 P1 O3 103.8(6) . . ?
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C14 O2 P1 123.7(10) . . ?
C6 C1 C2 125.8(17) . . ?
C6 C1 O3 118.5(17) . . ?
C2 C1 O3 114.6(16) . . ?
C1 C2 C3 113.4(17) . . ?
C1 C2 C22 126.7(18) . . ?
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C4 C5 C6 121.7(19) . . ?
C1 C6 C5 116.4(18) . . ?
C1 C6 C7 124.5(15) . . ?
C5 C6 C7 119.1(16) . . ?
C6 C7 C8 110.3(14) . . ?
C9 C8 C13 116.1(19) . . ?
C9 C8 C7 127.6(17) . . ?
C13 C8 C7 116.0(15) . . ?
C8 C9 C10 127.3(18) . . ?
C8 C9 O1 117.5(18) . . ?
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C12 C11 C10 125(2) . . ?
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C12 C13 C8 122.0(17) . . ?
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C2 C22 C24 113.2(15) . . ?
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C25 C22 C24 106.7(19) . . ?
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C29 C28 C10 113.5(18) . . ?
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C10 C28 C30 110.3(18) . . ?
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Appendix 5

X-ray data for complex 58

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 'Cl'  'Cl'   0.1484   0.1585
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 'Pd'  'Pd'   -1.1770   1.0070
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 '-x, -y, -z'

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_cell_length_b                      11.5041(16)
_cell_length_c                      13.345(2)
_cell_angle_alpha                   86.566(14)
_cell_angle_beta                    69.9550(10)
_cell_angle_gamma                   81.990(9)
_cell_volume                        1498.1(3)
_cell_formula_units_Z               2
_cell_measurement_temperature       293(2)
_cell_measurement_reflns_used       ?
_cell_measurement_theta_min         ?
_cell_measurement_theta_max         ?

_exptl_crystal_description          ?
_exptl_crystal_colour               ?
_exptl_crystal_size_max             ?
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 Refinement of F^2^ against ALL reflections.  The weighted R-factor wR and
 goodness of fit S are based on F^2^, conventional R-factors R are based
 on F, with F set to zero for negative F^2^. The threshold expression of
 F^2^ > 2sigma(F^2^) is used only for calculating R-factors(gt) etc. and is
 not relevant to the choice of reflections for refinement.  R-factors based
 on F^2^ are statistically about twice as large as those based on F, and R-
 factors based on ALL data will be even larger.
;
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'calc w=1/[\s^2^(Fo^2^)+(0.0503P)^2^+0.0102P] where P=(Fo^2^+2Fc^2^)/3'
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_atom_sites_solution_secondary    difmap
_atom_sites_solution_hydrogens    geom
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P1 P 0.52767(9) 0.27731(7) 0.21003(7) 0.0363(2) Uani 1 1 d . . .
Cl1 Cl 0.37104(12) 0.59946(9) 0.05257(8) 0.0680(3) Uani 1 1 d . . .
O3 O 0.5026(2) 0.3197(2) 0.32825(18) 0.0437(6) Uani 1 1 d . . .
O4 O 0.4355(2) 0.1746(2) 0.22709(19) 0.0443(6) Uani 1 1 d . . .
O8 O 0.6783(2) 0.2142(2) 0.18462(17) 0.0379(5) Uani 1 1 d . . .
C1 C 0.3479(4) 0.4640(3) 0.2770(3) 0.0428(9) Uani 1 1 d . . .
C2 C 0.3910(4) 0.4105(3) 0.3574(3) 0.0404(8) Uani 1 1 d . . .
C3 C 0.3318(4) 0.4399(4) 0.4645(3) 0.0498(10) Uani 1 1 d . . .
C4 C 0.2213(5) 0.5271(4) 0.4874(4) 0.0603(12) Uani 1 1 d . . .
C5 C 0.1679(4) 0.5798(4) 0.4124(3) 0.0573(11) Uani 1 1 d . . .
C6 C 0.2333(4) 0.5478(3) 0.3062(3) 0.0505(10) Uani 1 1 d . . .
C7 C 0.6227(4) 0.0983(4) 0.0235(3) 0.0447(9) Uani 1 1 d . . .
C8 C 0.5712(3) 0.0154(3) 0.1169(3) 0.0402(8) Uani 1 1 d . . .
C9 C 0.6144(4) -0.1044(3) 0.1024(3) 0.0463(9) Uani 1 1 d . . .
C10 C 0.5654(4) -0.1844(3) 0.1829(4) 0.0524(10) Uani 1 1 d . . .
C11 C 0.4681(4) -0.1433(4) 0.2773(4) 0.0547(11) Uani 1 1 d . . .
C12 C 0.4196(4) -0.0251(3) 0.2975(3) 0.0465(9) Uani 1 1 d . . .
C13 C 0.4782(3) 0.0529(3) 0.2140(3) 0.0400(8) Uani 1 1 d . . .
C14 C 0.7847(3) 0.1962(3) 0.0850(2) 0.0358(8) Uani 1 1 d . . .
C15 C 0.9094(4) 0.2348(3) 0.0723(3) 0.0400(8) Uani 1 1 d . . .
C16 C 1.0100(4) 0.2101(4) -0.0261(3) 0.0471(9) Uani 1 1 d . . .
C17 C 0.9912(4) 0.1495(4) -0.1058(3) 0.0509(10) Uani 1 1 d . . .
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C18 C 0.8664(4) 0.1137(4) -0.0870(3) 0.0481(10) Uani 1 1 d . . .
C19 C 0.7606(4) 0.1357(3) 0.0083(3) 0.0387(8) Uani 1 1 d . . .
C20 C 0.3844(7) 0.3827(6) 0.5479(4) 0.0718(16) Uani 1 1 d . . .
C21 C 0.0439(7) 0.6708(6) 0.4439(7) 0.0832(18) Uani 1 1 d . . .
C22 C 0.9358(4) 0.3026(3) 0.1587(3) 0.0488(9) Uani 1 1 d . . .
C23 C 0.9051(6) 0.2306(5) 0.2619(4) 0.0643(13) Uani 1 1 d . . .
C24 C 1.0841(6) 0.3257(7) 0.1259(5) 0.0764(16) Uani 1 1 d . . .
C25 C 0.8455(7) 0.4209(5) 0.1770(5) 0.0699(14) Uani 1 1 d . . .
C26 C 0.3021(4) 0.0138(4) 0.3985(3) 0.0574(11) Uani 1 1 d . . .
C27 C 0.2618(8) -0.0899(6) 0.4762(6) 0.095(2) Uani 1 1 d . . .
C28 C 0.3363(9) 0.1041(6) 0.4609(5) 0.096(2) Uani 1 1 d . . .
C29 C 0.1785(6) 0.0659(9) 0.3678(6) 0.105(2) Uani 1 1 d . . .
C30 C 0.6163(7) -0.3134(4) 0.1681(6) 0.0761(15) Uani 1 1 d . . .
C31 C 1.1065(6) 0.1239(7) -0.2105(4) 0.0749(15) Uani 1 1 d . . .
H3 H 0.176(4) 0.540(3) 0.552(3) 0.053(11) Uiso 1 1 d . . .
H5 H 0.195(4) 0.587(4) 0.255(3) 0.057(13) Uiso 1 1 d . . .
H7A H 0.565(3) 0.157(3) 0.027(2) 0.026(8) Uiso 1 1 d . . .
H7B H 0.630(4) 0.061(3) -0.037(3) 0.052(11) Uiso 1 1 d . . .
H9 H 0.676(4) -0.119(3) 0.041(3) 0.033(10) Uiso 1 1 d . . .
H11 H 0.426(4) -0.191(4) 0.325(3) 0.058(13) Uiso 1 1 d . . .
H16 H 1.091(3) 0.231(3) -0.039(2) 0.026(9) Uiso 1 1 d . . .
H18 H 0.850(3) 0.076(3) -0.131(3) 0.031(10) Uiso 1 1 d . . .
H20A H 0.469(6) 0.354(5) 0.528(4) 0.10(2) Uiso 1 1 d . . .
H20B H 0.360(5) 0.417(5) 0.599(4) 0.086(18) Uiso 1 1 d . . .
H20C H 0.348(6) 0.313(6) 0.569(5) 0.11(2) Uiso 1 1 d . . .
H21A H 0.059(7) 0.737(6) 0.399(5) 0.13(3) Uiso 1 1 d . . .
H21B H -0.009(6) 0.647(5) 0.412(5) 0.10(2) Uiso 1 1 d . . .
H21C H -0.003(6) 0.661(5) 0.506(5) 0.12(2) Uiso 1 1 d . . .
H23A H 0.929(4) 0.265(4) 0.309(4) 0.065(14) Uiso 1 1 d . . .
H23B H 0.811(5) 0.219(4) 0.294(3) 0.061(12) Uiso 1 1 d . . .
H23C H 0.965(6) 0.156(5) 0.245(4) 0.097(19) Uiso 1 1 d . . .
H24A H 1.101(5) 0.371(4) 0.069(4) 0.073(16) Uiso 1 1 d . . .
H24B H 1.141(5) 0.255(5) 0.117(4) 0.092(18) Uiso 1 1 d . . .
H24C H 1.097(5) 0.364(4) 0.182(4) 0.077(14) Uiso 1 1 d . . .
H25A H 0.869(5) 0.464(4) 0.225(4) 0.076(15) Uiso 1 1 d . . .
H25B H 0.863(7) 0.461(6) 0.116(6) 0.13(3) Uiso 1 1 d . . .
H25C H 0.760(6) 0.416(5) 0.202(4) 0.08(2) Uiso 1 1 d . . .
H27A H 0.202(5) -0.067(4) 0.533(4) 0.082(16) Uiso 1 1 d . . .
H27B H 0.239(5) -0.147(5) 0.427(4) 0.096(18) Uiso 1 1 d . . .
H27C H 0.336(8) -0.140(7) 0.487(6) 0.15(3) Uiso 1 1 d . . .
H28A H 0.365(6) 0.173(5) 0.431(4) 0.126(19) Uiso 1 1 d . . .
H28B H 0.280(6) 0.122(5) 0.520(5) 0.10(2) Uiso 1 1 d . . .
H28C H 0.445(6) 0.072(5) 0.469(4) 0.11(2) Uiso 1 1 d . . .
H29A H 0.195(5) 0.126(5) 0.324(4) 0.076(19) Uiso 1 1 d . . .
H29B H 0.110(6) 0.083(5) 0.439(5) 0.109(19) Uiso 1 1 d . . .
H29C H 0.166(6) -0.008(6) 0.343(5) 0.12(3) Uiso 1 1 d . . .
H30A H 0.559(5) -0.364(5) 0.204(4) 0.085(16) Uiso 1 1 d . . .
H30B H 0.644(5) -0.334(5) 0.090(4) 0.100(18) Uiso 1 1 d . . .
H30C H 0.704(6) -0.335(5) 0.175(4) 0.11(2) Uiso 1 1 d . . .
H31A H 1.136(5) 0.195(4) -0.234(3) 0.072(15) Uiso 1 1 d . . .
H31B H 1.072(7) 0.108(6) -0.259(6) 0.12(3) Uiso 1 1 d . . .
H31C H 1.175(6) 0.075(5) -0.203(4) 0.09(2) Uiso 1 1 d . . .

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Cl1 0.0829(8) 0.0558(6) 0.0399(5) 0.0103(4) -0.0051(5) 0.0300(6)
O3 0.0439(14) 0.0469(14) 0.0352(13) 0.0010(11) -0.0103(11) 0.0029(11)
O4 0.0368(13) 0.0337(13) 0.0566(15) 0.0048(11) -0.0112(12) 0.0013(10)
O8 0.0360(13) 0.0411(13) 0.0324(12) 0.0014(10) -0.0088(10) 0.0012(10)
C1 0.048(2) 0.0345(19) 0.040(2) -0.0023(15) -0.0084(17) -0.0022(16)
C2 0.039(2) 0.0370(19) 0.040(2) -0.0019(15) -0.0068(16) -0.0041(16)
C3 0.052(2) 0.055(2) 0.037(2) -0.0072(17) -0.0058(18) -0.0095(19)
C4 0.061(3) 0.065(3) 0.040(2) -0.015(2) 0.001(2) -0.001(2)
C5 0.049(2) 0.046(2) 0.063(3) -0.011(2) -0.002(2) 0.0000(19)
C6 0.048(2) 0.044(2) 0.051(2) -0.0011(18) -0.007(2) -0.0005(18)
C7 0.047(2) 0.042(2) 0.046(2) -0.0005(18) -0.0206(19) 0.0024(19)
C8 0.0349(19) 0.040(2) 0.052(2) 0.0028(16) -0.0232(17) -0.0034(15)
C9 0.037(2) 0.045(2) 0.057(3) -0.0086(19) -0.016(2) -0.0013(17)
C10 0.046(2) 0.038(2) 0.077(3) 0.001(2) -0.026(2) -0.0047(17)
C11 0.047(2) 0.039(2) 0.074(3) 0.014(2) -0.016(2) -0.0104(19)
C12 0.039(2) 0.038(2) 0.064(2) 0.0085(17) -0.0208(18) -0.0055(16)
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C14 0.0374(19) 0.0347(18) 0.0308(17) 0.0011(14) -0.0094(15) 0.0042(15)
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C17 0.047(2) 0.060(3) 0.038(2) -0.0069(18) -0.0063(17) 0.0022(19)
C18 0.052(3) 0.053(2) 0.042(2) -0.0079(19) -0.019(2) -0.0006(19)
C19 0.042(2) 0.0349(19) 0.0378(19) 0.0024(15) -0.0148(16) 0.0006(15)
C20 0.081(4) 0.093(4) 0.039(3) -0.007(3) -0.019(3) -0.004(3)
C21 0.064(4) 0.075(4) 0.087(4) -0.018(4) 0.000(4) 0.013(3)
C22 0.047(2) 0.051(2) 0.046(2) -0.0084(17) -0.0129(18) -0.0019(18)
C23 0.071(4) 0.082(4) 0.050(3) -0.001(2) -0.033(3) -0.009(3)
C24 0.061(3) 0.098(5) 0.073(4) -0.023(4) -0.016(3) -0.024(3)
C25 0.088(5) 0.048(3) 0.074(4) -0.018(3) -0.028(3) 0.002(3)
C26 0.048(2) 0.053(3) 0.059(3) 0.011(2) -0.004(2) -0.0100(19)
C27 0.099(5) 0.066(4) 0.079(4) 0.016(3) 0.020(4) -0.014(3)
C28 0.118(6) 0.091(4) 0.058(3) -0.001(3) 0.008(4) -0.038(4)
C29 0.050(3) 0.132(7) 0.100(5) 0.020(5) 0.001(3) 0.015(4)
C30 0.077(4) 0.035(2) 0.106(5) -0.002(3) -0.019(3) -0.004(2)
C31 0.063(3) 0.105(5) 0.051(3) -0.020(3) -0.009(3) -0.010(3)

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 All esds (except the esd in the dihedral angle between two l.s. planes)
 are estimated using the full covariance matrix.  The cell esds are taken
 into account individually in the estimation of esds in distances, angles
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 used when they are defined by crystal symmetry.  An approximate (isotropic)
 treatment of cell esds is used for estimating esds involving l.s. planes.
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Pd P1 2.1585(9) . ?
Pd Cl1 2.3894(10) . ?
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P1 O8 1.576(2) . ?
P1 O4 1.588(3) . ?
P1 O3 1.603(2) . ?
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O3 C2 1.417(4) . ?
O4 C13 1.411(4) . ?
O8 C14 1.417(4) . ?
C1 C2 1.383(5) . ?
C1 C6 1.387(5) . ?
C2 C3 1.391(5) . ?
C3 C4 1.384(6) . ?
C3 C20 1.486(7) . ?
C4 C5 1.378(6) . ?
C5 C6 1.394(6) . ?
C5 C21 1.505(7) . ?
C7 C19 1.510(5) . ?
C7 C8 1.515(5) . ?
C8 C13 1.379(5) . ?
C8 C9 1.392(5) . ?
C9 C10 1.378(6) . ?
C10 C11 1.382(6) . ?
C10 C30 1.505(6) . ?
C11 C12 1.391(5) . ?
C12 C13 1.410(5) . ?
C12 C26 1.522(5) . ?
C14 C19 1.381(5) . ?
C14 C15 1.392(5) . ?
C15 C16 1.389(5) . ?
C15 C22 1.549(5) . ?
C16 C17 1.388(6) . ?
C17 C18 1.364(6) . ?
C17 C31 1.514(6) . ?
C18 C19 1.381(5) . ?
C22 C23 1.523(6) . ?
C22 C24 1.522(7) . ?
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C26 C29 1.525(8) . ?
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C1 Pd P1 78.06(10) . . ?
C1 Pd Cl1 94.38(10) . . ?
P1 Pd Cl1 172.17(3) . . ?
C1 Pd Cl1 171.94(11) . 2_665 ?
P1 Pd Cl1 102.39(4) . 2_665 ?
Cl1 Pd Cl1 85.38(4) . 2_665 ?
O8 P1 O4 105.32(13) . . ?
O8 P1 O3 98.29(13) . . ?
O4 P1 O3 104.43(14) . . ?
O8 P1 Pd 125.51(9) . . ?
O4 P1 Pd 113.60(10) . . ?
O3 P1 Pd 106.83(9) . . ?
Pd Cl1 Pd 94.62(4) . 2_665 ?
C2 O3 P1 109.4(2) . . ?
C13 O4 P1 128.1(2) . . ?
C14 O8 P1 129.5(2) . . ?
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C2 C1 C6 117.6(3) . . ?
C2 C1 Pd 117.9(3) . . ?
C6 C1 Pd 124.2(3) . . ?
C1 C2 C3 124.2(3) . . ?
C1 C2 O3 117.6(3) . . ?
C3 C2 O3 118.2(3) . . ?
C4 C3 C2 115.0(4) . . ?
C4 C3 C20 122.5(4) . . ?
C2 C3 C20 122.5(4) . . ?
C5 C4 C3 124.0(4) . . ?
C4 C5 C6 118.1(4) . . ?
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C1 C6 C5 120.9(4) . . ?
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C13 C8 C9 118.6(3) . . ?
C13 C8 C7 122.7(3) . . ?
C9 C8 C7 118.6(4) . . ?
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C11 C12 C26 121.4(4) . . ?
C13 C12 C26 123.2(3) . . ?
C8 C13 O4 117.7(3) . . ?
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O4 C13 C12 119.3(3) . . ?
C19 C14 C15 124.0(3) . . ?
C19 C14 O8 117.8(3) . . ?
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C18 C19 C7 119.7(3) . . ?
C14 C19 C7 122.5(3) . . ?
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C12 C26 C29 108.7(4) . . ?
C12 C26 C28 113.2(4) . . ?
C29 C26 C28 109.0(6) . . ?
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C28 C26 C27 105.8(5) . . ?

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_diffrn_reflns_theta_full              25.05
_diffrn_measured_fraction_theta_full   0.965
_refine_diff_density_max    0.341
_refine_diff_density_min   -0.372
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_refine_diff_density_rms     0.070
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Appendix 6

X-ray data for complex 61

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data_rupcps

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;
_chemical_name_common             ?
_chemical_melting_point           ?
_chemical_formula_moiety          ?
_chemical_formula_sum
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_chemical_formula_weight          904.22

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 _atom_type_description
 _atom_type_scat_dispersion_real
 _atom_type_scat_dispersion_imag
 _atom_type_scat_source
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 'International Tables Vol C Tables 4.2.6.8 and 6.1.1.4'
 'H'  'H'   0.0000   0.0000
 'International Tables Vol C Tables 4.2.6.8 and 6.1.1.4'
 'Cl'  'Cl'   0.1484   0.1585
 'International Tables Vol C Tables 4.2.6.8 and 6.1.1.4'
 'O'  'O'   0.0106   0.0060
 'International Tables Vol C Tables 4.2.6.8 and 6.1.1.4'
 'P'  'P'   0.1023   0.0942
 'International Tables Vol C Tables 4.2.6.8 and 6.1.1.4'
 'Ru'  'Ru'  -1.2594   0.8363
 'International Tables Vol C Tables 4.2.6.8 and 6.1.1.4'

_symmetry_cell_setting            ?
_symmetry_space_group_name_H-M    ?

loop_
 _symmetry_equiv_pos_as_xyz
 'x, y, z'
 '-x+1/2, y+1/2, -z+1/2'
 '-x, -y, -z'
 'x-1/2, -y-1/2, z-1/2'

_cell_length_a                    10.0759(12)
_cell_length_b                    20.2499(18)
_cell_length_c                    20.470(14)
_cell_angle_alpha                 90.00
_cell_angle_beta                  92.71(3)
_cell_angle_gamma                 90.00
_cell_volume                      4172(3)
_cell_formula_units_Z             4
_cell_measurement_temperature     293(2)
_cell_measurement_reflns_used     ?
_cell_measurement_theta_min       ?
_cell_measurement_theta_max       ?

_exptl_crystal_description        ?
_exptl_crystal_colour             ?
_exptl_crystal_size_max           ?
_exptl_crystal_size_mid           ?
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_exptl_crystal_size_min                 ?
_exptl_crystal_density_meas             ?
_exptl_crystal_density_diffrn           1.440
_exptl_crystal_density_method           'not measured'
_exptl_crystal_F_000                    1848
_exptl_absorpt_coefficient_mu           0.598
_exptl_absorpt_correction_type          ?
_exptl_absorpt_correction_T_min         ?
_exptl_absorpt_correction_T_max         ?
_exptl_absorpt_process_details          ?

_exptl_special_details
;
 ?
;

_diffrn_ambient_temperature             293(2)
_diffrn_radiation_wavelength            0.71073
_diffrn_radiation_type                  MoK\a
_diffrn_radiation_source                'fine-focus sealed tube'
_diffrn_radiation_monochromator         graphite
_diffrn_measurement_device_type         ?
_diffrn_measurement_method              ?
_diffrn_detector_area_resol_mean        ?
_diffrn_standards_number                ?
_diffrn_standards_interval_count        ?
_diffrn_standards_interval_time         ?
_diffrn_standards_decay_%               ?
_diffrn_reflns_number                   7482
_diffrn_reflns_av_R_equivalents         0.0178
_diffrn_reflns_av_sigmaI/netI           0.0228
_diffrn_reflns_limit_h_min              0
_diffrn_reflns_limit_h_max              11
_diffrn_reflns_limit_k_min              0
_diffrn_reflns_limit_k_max              21
_diffrn_reflns_limit_l_min              -21
_diffrn_reflns_limit_l_max              21
_diffrn_reflns_theta_min                1.42
_diffrn_reflns_theta_max                25.02
_reflns_number_total                    7073
_reflns_number_gt                       5992
_reflns_threshold_expression            >2sigma(I)

_computing_data_collection              ?
_computing_cell_refinement              ?
_computing_data_reduction               ?
_computing_structure_solution           ?
_computing_structure_refinement         'SHELXL-97 (Sheldrick, 1997)'
_computing_molecular_graphics           ?
_computing_publication_material         ?

_refine_special_details
;
 Refinement of F^2^ against ALL reflections.  The weighted R-factor wR and
 goodness of fit S are based on F^2^, conventional R-factors R are based
 on F, with F set to zero for negative F^2^. The threshold expression of
 F^2^ > 2sigma(F^2^) is used only for calculating R-factors(gt) etc. and is
 not relevant to the choice of reflections for refinement.  R-factors based
 on F^2^ are statistically about twice as large as those based on F, and R-
 factors based on ALL data will be even larger.
;
```

```
_refine_ls_structure_factor_coef Fsqd
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_refine_ls_weighting_details
 'calc w=1/[\s^2^(Fo^2^)+(0.0524P)^2^+3.2983P] where P=(Fo^2^+2Fc^2^)/3'
_atom_sites_solution_primary     direct
_atom_sites_solution_secondary   difmap
_atom_sites_solution_hydrogens   geom
_refine_ls_hydrogen_treatment    mixed
_refine_ls_extinction_method     none
_refine_ls_extinction_coef       ?
_refine_ls_number_reflns         7073
_refine_ls_number_parameters     666
_refine_ls_number_restraints     0
_refine_ls_R_factor_all          0.0421
_refine_ls_R_factor_gt           0.0297
_refine_ls_wR_factor_ref         0.0828
_refine_ls_wR_factor_gt          0.0759
_refine_ls_goodness_of_fit_ref   0.930
_refine_ls_restrained_S_all      0.930
_refine_ls_shift/su_max          0.038
_refine_ls_shift/su_mean         0.004

loop_
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 _atom_site_type_symbol
 _atom_site_fract_x
 _atom_site_fract_y
 _atom_site_fract_z
 _atom_site_U_iso_or_equiv
 _atom_site_adp_type
 _atom_site_occupancy
 _atom_site_symmetry_multiplicity
 _atom_site_calc_flag
 _atom_site_refinement_flags
 _atom_site_disorder_assembly
 _atom_site_disorder_group
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Cl1 Cl 0.68993(8) 0.73642(4) 0.70359(4) 0.0554(2) Uani 1 1 d . . .
P1 P 0.76806(6) 0.67431(3) 0.54737(3) 0.03161(15) Uani 1 1 d . . .
P2 P 1.00771(7) 0.70295(3) 0.69511(4) 0.03629(16) Uani 1 1 d . . .
P3 P 0.74169(7) 0.85299(3) 0.58092(4) 0.03520(16) Uani 1 1 d . . .
O1 O 1.0752(2) 0.75999(9) 0.74309(10) 0.0450(5) Uani 1 1 d . . .
O2 O 0.8085(2) 0.91574(9) 0.62155(10) 0.0438(5) Uani 1 1 d . . .
O3 O 1.0766(2) 0.78718(13) 0.53978(14) 0.0661(7) Uani 1 1 d . . .
C1 C 1.0027(3) 0.77745(13) 0.56801(13) 0.0368(6) Uani 1 1 d . . .
C2 C 0.9363(3) 0.83533(13) 0.68212(13) 0.0336(6) Uani 1 1 d . . .
C3 C 0.9042(3) 0.90082(13) 0.67034(13) 0.0358(6) Uani 1 1 d . . .
C4 C 0.9655(3) 0.95311(14) 0.70384(15) 0.0439(7) Uani 1 1 d . . .
C5 C 1.0634(3) 0.93910(15) 0.75049(15) 0.0478(8) Uani 1 1 d . . .
C6 C 1.1008(3) 0.87466(15) 0.76438(14) 0.0424(7) Uani 1 1 d . . .
C7 C 1.0362(3) 0.82461(13) 0.72965(13) 0.0372(6) Uani 1 1 d . . .
C100 C 0.8728(3) 0.65627(14) 0.47827(13) 0.0385(6) Uani 1 1 d . . .
C101 C 0.9295(3) 0.59500(17) 0.46741(16) 0.0499(8) Uani 1 1 d . . .
C102 C 1.0057(4) 0.5846(2) 0.4140(2) 0.0670(11) Uani 1 1 d . . .
C103 C 1.0269(4) 0.6348(2) 0.3706(2) 0.0731(11) Uani 1 1 d . . .
C104 C 0.9741(4) 0.6957(2) 0.38158(19) 0.0678(10) Uani 1 1 d . . .
C105 C 0.8987(3) 0.70663(18) 0.43529(16) 0.0520(8) Uani 1 1 d . . .
C200 C 0.7283(2) 0.59177(13) 0.57788(13) 0.0332(6) Uani 1 1 d . . .
C201 C 0.6730(3) 0.54299(14) 0.53670(16) 0.0414(6) Uani 1 1 d . . .
```

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C202 C 0.6421(3) 0.48194(15) 0.56144(17) 0.0464(7) Uani 1 1 d . . .
C203 C 0.6630(3) 0.46866(15) 0.62684(17) 0.0492(8) Uani 1 1 d . . .
C204 C 0.7157(3) 0.51662(16) 0.66780(17) 0.0493(7) Uani 1 1 d . . .
C205 C 0.7473(3) 0.57772(15) 0.64345(15) 0.0418(7) Uani 1 1 d . . .
C300 C 0.6076(2) 0.69407(13) 0.50603(13) 0.0347(6) Uani 1 1 d . . .
C301 C 0.5097(3) 0.71775(16) 0.54506(17) 0.0452(7) Uani 1 1 d . . .
C302 C 0.3835(3) 0.73061(19) 0.5187(2) 0.0599(9) Uani 1 1 d . . .
C303 C 0.3550(3) 0.71952(18) 0.4532(2) 0.0623(10) Uani 1 1 d . . .
C304 C 0.4507(3) 0.69597(16) 0.41400(18) 0.0542(8) Uani 1 1 d . . .
C305 C 0.5768(3) 0.68300(15) 0.44073(15) 0.0451(7) Uani 1 1 d . . .
C400 C 0.7787(3) 0.87589(13) 0.49809(14) 0.0398(6) Uani 1 1 d . . .
C401 C 0.8909(3) 0.91334(18) 0.48724(18) 0.0552(8) Uani 1 1 d . . .
C402 C 0.9262(4) 0.9265(2) 0.4245(2) 0.0763(12) Uani 1 1 d . . .
C403 C 0.8503(5) 0.9032(2) 0.3719(2) 0.0774(12) Uani 1 1 d . . .
C404 C 0.7394(4) 0.8659(2) 0.38209(18) 0.0629(10) Uani 1 1 d . . .
C405 C 0.7034(3) 0.85215(16) 0.44473(16) 0.0477(7) Uani 1 1 d . . .
C500 C 0.5663(3) 0.87424(14) 0.58731(16) 0.0460(7) Uani 1 1 d . . .
C501 C 0.5050(4) 0.85681(18) 0.6439(2) 0.0678(10) Uani 1 1 d . . .
C502 C 0.3735(4) 0.8737(2) 0.6523(3) 0.0846(14) Uani 1 1 d . . .
C503 C 0.3041(4) 0.9085(3) 0.6056(3) 0.0887(15) Uani 1 1 d . . .
C504 C 0.3639(4) 0.9283(3) 0.5512(3) 0.0917(16) Uani 1 1 d . . .
C505 C 0.4962(4) 0.9112(2) 0.5415(2) 0.0683(11) Uani 1 1 d . . .
C600 C 1.1524(3) 0.66328(14) 0.66419(15) 0.0441(7) Uani 1 1 d . . .
C601 C 1.1351(4) 0.62092(19) 0.61241(19) 0.0638(10) Uani 1 1 d . . .
C602 C 1.2390(4) 0.5822(2) 0.5928(2) 0.0753(12) Uani 1 1 d . . .
C603 C 1.3604(4) 0.5867(2) 0.6245(2) 0.0704(11) Uani 1 1 d . . .
C604 C 1.3807(3) 0.6300(2) 0.6746(2) 0.0665(11) Uani 1 1 d . . .
C605 C 1.2769(3) 0.66856(18) 0.69523(18) 0.0539(8) Uani 1 1 d . . .
C700 C 0.9615(3) 0.64457(14) 0.75793(15) 0.0457(7) Uani 1 1 d . . .
C701 C 0.8882(4) 0.66696(19) 0.80891(17) 0.0586(9) Uani 1 1 d . . .
C702 C 0.8501(5) 0.6241(3) 0.8575(2) 0.0840(14) Uani 1 1 d . . .
C703 C 0.8837(6) 0.5594(3) 0.8547(3) 0.0974(18) Uani 1 1 d . . .
C704 C 0.9561(6) 0.5365(2) 0.8062(3) 0.0887(16) Uani 1 1 d . . .
C705 C 0.9975(4) 0.57823(17) 0.7565(2) 0.0633(10) Uani 1 1 d . . .
H4 H 0.940(3) 0.9973(15) 0.6934(12) 0.035(7) Uiso 1 1 d . . .
H5 H 1.108(3) 0.9704(17) 0.7732(15) 0.053(9) Uiso 1 1 d . . .
H6 H 1.165(3) 0.8640(15) 0.7934(15) 0.043(8) Uiso 1 1 d . . .
H101 H 0.911(3) 0.5582(16) 0.4951(15) 0.047(9) Uiso 1 1 d . . .
H102 H 1.038(4) 0.550(2) 0.4078(18) 0.066(12) Uiso 1 1 d . . .
H103 H 1.075(4) 0.6247(19) 0.3307(19) 0.080(12) Uiso 1 1 d . . .
H104 H 0.985(4) 0.7298(19) 0.3563(19) 0.070(12) Uiso 1 1 d . . .
H105 H 0.871(3) 0.7460(15) 0.4440(15) 0.039(8) Uiso 1 1 d . . .
H201 H 0.657(3) 0.5532(15) 0.4940(15) 0.044(8) Uiso 1 1 d . . .
H202 H 0.606(3) 0.4514(16) 0.5327(15) 0.053(9) Uiso 1 1 d . . .
H203 H 0.641(3) 0.4292(17) 0.6414(15) 0.052(9) Uiso 1 1 d . . .
H204 H 0.727(3) 0.5090(15) 0.7099(15) 0.044(9) Uiso 1 1 d . . .
H205 H 0.780(3) 0.6084(15) 0.6718(15) 0.045(8) Uiso 1 1 d . . .
H301 H 0.530(3) 0.7254(14) 0.5878(15) 0.039(8) Uiso 1 1 d . . .
H302 H 0.323(4) 0.7468(16) 0.5450(17) 0.059(10) Uiso 1 1 d . . .
H303 H 0.268(4) 0.726(2) 0.4372(19) 0.082(12) Uiso 1 1 d . . .
H304 H 0.430(3) 0.6876(17) 0.3675(17) 0.063(10) Uiso 1 1 d . . .
H305 H 0.638(3) 0.6679(14) 0.4142(14) 0.039(8) Uiso 1 1 d . . .
H401 H 0.939(3) 0.9267(17) 0.5202(17) 0.058(10) Uiso 1 1 d . . .
H402 H 1.000(4) 0.953(2) 0.418(2) 0.092(14) Uiso 1 1 d . . .
H403 H 0.880(4) 0.911(2) 0.331(2) 0.086(13) Uiso 1 1 d . . .
H404 H 0.693(4) 0.8512(18) 0.3492(18) 0.067(11) Uiso 1 1 d . . .
H405 H 0.630(3) 0.8251(16) 0.4527(15) 0.053(9) Uiso 1 1 d . . .
H501 H 0.559(4) 0.8341(19) 0.6785(18) 0.076(12) Uiso 1 1 d . . .
H502 H 0.337(5) 0.862(2) 0.692(2) 0.110(17) Uiso 1 1 d . . .
H503 H 0.215(5) 0.921(3) 0.615(3) 0.130(19) Uiso 1 1 d . . .
H504 H 0.327(5) 0.949(2) 0.519(2) 0.096(16) Uiso 1 1 d . . .
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H505 H 0.530(4) 0.923(2) 0.507(2) 0.079(14) Uiso 1 1 d . . .
H601 H 1.048(4) 0.6183(19) 0.5898(18) 0.076(12) Uiso 1 1 d . . .
H602 H 1.229(5) 0.555(2) 0.559(2) 0.108(17) Uiso 1 1 d . . .
H603 H 1.431(5) 0.565(2) 0.608(2) 0.106(16) Uiso 1 1 d . . .
H604 H 1.456(4) 0.634(2) 0.695(2) 0.091(14) Uiso 1 1 d . . .
H605 H 1.287(3) 0.6943(17) 0.7296(16) 0.056(10) Uiso 1 1 d . . .
H701 H 0.863(4) 0.712(2) 0.8098(17) 0.066(11) Uiso 1 1 d . . .
H702 H 0.809(5) 0.642(3) 0.892(3) 0.12(2) Uiso 1 1 d . . .
H703 H 0.856(5) 0.530(3) 0.887(2) 0.113(17) Uiso 1 1 d . . .
H704 H 0.991(4) 0.499(2) 0.798(2) 0.086(14) Uiso 1 1 d . . .
H705 H 1.046(3) 0.5646(16) 0.7205(15) 0.046(9) Uiso 1 1 d . . .

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Cl1 0.0540(5) 0.0554(5) 0.0574(5) 0.0015(4) 0.0095(4) 0.0050(4)
P1 0.0279(3) 0.0299(3) 0.0371(4) -0.0037(3) 0.0022(3) 0.0007(3)
P2 0.0365(4) 0.0300(4) 0.0416(4) -0.0030(3) -0.0058(3) 0.0019(3)
P3 0.0317(3) 0.0291(4) 0.0450(4) 0.0008(3) 0.0043(3) 0.0037(3)
O1 0.0484(12) 0.0370(11) 0.0479(12) -0.0040(9) -0.0138(9) -0.0021(9)
O2 0.0493(11) 0.0278(10) 0.0540(12) -0.0021(8) -0.0008(9) 0.0039(8)
O3 0.0452(14) 0.0663(17) 0.0864(19) -0.0045(14) -0.0018(13) 0.0039(12)
C1 0.0531(18) 0.0260(14) 0.0308(15) -0.0040(11) -0.0019(13) 0.0111(13)
C2 0.0353(14) 0.0294(14) 0.0366(14) -0.0063(10) 0.0080(11) -0.0048(11)
C3 0.0391(14) 0.0328(14) 0.0362(15) -0.0058(11) 0.0092(11) -0.0024(11)
C4 0.0569(18) 0.0289(15) 0.0469(18) -0.0070(12) 0.0142(14) -0.0087(13)
C5 0.0576(19) 0.0426(18) 0.0440(17) -0.0122(13) 0.0101(14) -0.0195(15)
C6 0.0472(17) 0.0437(17) 0.0363(16) -0.0068(12) 0.0034(13) -0.0103(13)
C7 0.0398(15) 0.0337(15) 0.0384(15) -0.0056(11) 0.0063(11) -0.0054(11)
C100 0.0303(13) 0.0462(16) 0.0391(15) -0.0073(12) 0.0032(11) 0.0005(11)
C101 0.0421(17) 0.053(2) 0.055(2) -0.0088(16) 0.0071(14) 0.0064(14)
C102 0.059(2) 0.066(3) 0.077(3) -0.020(2) 0.0182(19) 0.0152(19)
C103 0.061(2) 0.099(3) 0.061(2) -0.017(2) 0.0230(19) 0.012(2)
C104 0.064(2) 0.086(3) 0.055(2) 0.009(2) 0.0169(18) -0.001(2)
C105 0.0511(18) 0.054(2) 0.052(2) -0.0036(15) 0.0091(14) 0.0039(16)
C200 0.0285(13) 0.0317(14) 0.0396(15) -0.0020(11) 0.0024(10) 0.0007(10)
C201 0.0397(15) 0.0384(16) 0.0457(18) -0.0062(13) -0.0011(13) -0.0004(12)
C202 0.0412(16) 0.0332(16) 0.065(2) -0.0117(14) 0.0054(14) -0.0042(12)
C203 0.0460(17) 0.0318(16) 0.071(2) 0.0035(14) 0.0098(15) -0.0056(13)
C204 0.0548(19) 0.0456(18) 0.0476(19) 0.0071(14) 0.0022(15) -0.0058(14)
C205 0.0407(16) 0.0379(16) 0.0468(17) -0.0041(13) 0.0001(13) -0.0063(12)
C300 0.0311(13) 0.0299(14) 0.0429(16) 0.0025(11) -0.0006(11) -0.0018(10)
C301 0.0347(15) 0.0501(18) 0.0507(19) -0.0005(14) 0.0014(13) 0.0002(13)
C302 0.0352(17) 0.065(2) 0.079(3) 0.0005(19) 0.0031(17) 0.0075(15)
C303 0.0415(18) 0.055(2) 0.088(3) 0.0095(18) -0.0238(18) 0.0004(15)
C304 0.060(2) 0.0445(18) 0.056(2) 0.0022(15) -0.0223(17) -0.0041(15)
C305 0.0480(17) 0.0398(16) 0.0470(18) -0.0018(13) -0.0028(14) -0.0019(13)
C400 0.0365(14) 0.0334(15) 0.0494(17) 0.0077(12) 0.0021(12) 0.0066(11)
C401 0.0501(19) 0.062(2) 0.053(2) 0.0069(16) 0.0010(16) -0.0118(16)
C402 0.071(3) 0.094(3) 0.064(3) 0.019(2) 0.011(2) -0.030(2)
C403 0.089(3) 0.098(3) 0.046(2) 0.015(2) 0.008(2) -0.017(2)
C404 0.072(2) 0.067(2) 0.049(2) 0.0060(17) -0.0130(18) 0.0040(19)
C405 0.0436(17) 0.0438(18) 0.055(2) 0.0062(14) -0.0052(14) 0.0019(14)
C500 0.0344(15) 0.0351(16) 0.069(2) -0.0051(14) 0.0077(14) 0.0051(12)
C501 0.059(2) 0.055(2) 0.092(3) 0.009(2) 0.030(2) 0.0178(17)
```

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C602 0.064(2) 0.073(3) 0.090(3) -0.026(2) 0.009(2) 0.021(2)
C603 0.051(2) 0.070(3) 0.091(3) 0.010(2) 0.017(2) 0.0234(19)
C604 0.0344(18) 0.081(3) 0.084(3) 0.020(2) 0.0011(18) 0.0070(17)
C605 0.0426(17) 0.060(2) 0.058(2) 0.0026(17) -0.0044(15) -0.0005(15)
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C701 0.075(2) 0.053(2) 0.048(2) 0.0067(15) -0.0040(17) -0.0102(18)
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 are estimated using the full covariance matrix.  The cell esds are taken
 into account individually in the estimation of esds in distances, angles
 and torsion angles; correlations between esds in cell parameters are only
 used when they are defined by crystal symmetry.  An approximate (isotropic)
 treatment of cell esds is used for estimating esds involving l.s. planes.
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P3 Ru1 P1 99.38(4) . . ?
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Appendix 7

X-ray data for complex 63

Table 1. Crystal data and structure refinement.

Identification code	00src233	
Empirical formula	$C_{83}H_{101}F_6O_4P_5Pd$	
Formula weight	1537.89	
Temperature	293(2) K	
Wavelength	0.71073 Å	
Crystal system	Triclinic	
Space group	$P\bar{1}$	
Unit cell dimensions	$a = 14.37030(2)$ Å	$\alpha = 71.2580(1)°$
	$b = 18.2612(2)$ Å	$\beta = 74.5800(1)°$
	$c = 19.31310(2)$ Å	$\gamma = 82.4990(1)°$
Volume	4620.97(5) $Å^3$	
Z	2	
Density (calculated)	1.105 Mg / m^3	
Absorption coefficient	0.340 mm^{-1}	
F(000)	1612	
Crystal	Block; colourless	
Crystal size	$0.15 \times 0.10 \times 0.10$ mm^3	
θ range for data collection	2.93 – 24.55°	
Index ranges	$-16 \leq h \leq 16, -19 \leq k \leq 21, -22 \leq l \leq 22$	
Reflections collected	36147	
Independent reflections	14919 [$R_{int} = 0.0557$]	
Completeness to $\theta = 24.55°$	96.3 %	
Max. and min. transmission	0.9667 and 0.9507	
Refinement method	Full-matrix least-squares on F^2	
Data / restraints / parameters	14919 / 115 / 918	
Goodness-of-fit on F^2	1.038	
Final R indices [$F^2 > 2\sigma(F^2)$]	$R1 = 0.0608$, $wR2 = 0.1255$	
R indices (all data)	$R1 = 0.0987$, $wR2 = 0.1348$	
Largest diff. peak and hole	0.932 and –0.558 e $Å^{-3}$	

Diffractometer: *Enraf Nonius KappaCCD* area detector (ϕ scans and ω scans to fill *Ewald* sphere). **Data collection and cell refinement:** *Denzo* (Z. Otwinowski & W. Minor, *Methods in Enzymology* (1997) Vol. **276**: *Macromolecular Crystallography*, part A, pp. 307–326; C. W. Carter, Jr. & R. M. Sweet, Eds., Academic Press). **Absorption correction:** *SORTAV* (R. H. Blessing, Acta Cryst. **A51** (1995) 33–37; R. H. Blessing, J. Appl. Cryst. **30** (1997) 421–426). **Program used to solve structure:** *SIR97* (Cascarano et al., Acta Cryst. **A52** (1996) C-79). **Program used to refine structure:** *SHELXL97* (G. M. Sheldrick (1997), University of Göttingen, Germany).
Further information: http://www.soton.ac.uk/~xservice/strat.htm

Special details:

Table 2. Atomic coordinates [× 10^4], equivalent isotropic displacement parameters [$Å^2 \times 10^3$] and site occupancy factors. U_{eq} is defined as one third of the trace of the orthogonalized U^{ij} tensor.

Atom	*x*	*y*	*z*	U_{eq}	*S.o.f.*
Pd1	8291(1)	3663(1)	8205(1)	40(1)	1
P1	7067(1)	3709(1)	9297(1)	46(1)	1
P2	9481(1)	3616(1)	8832(1)	43(1)	1
P3	7570(1)	2435(1)	11599(1)	61(1)	1
P4	7318(1)	3772(1)	7427(1)	42(1)	1
O4	6621(2)	3115(2)	7538(2)	59(1)	1
O1	6589(3)	2801(2)	11737(2)	82(1)	1
O2	8003(2)	3902(2)	6605(2)	51(1)	1
O3	6535(2)	4451(2)	7263(2)	47(1)	1
C1	7354(3)	4000(3)	10043(3)	50(1)	1
C2	8290(3)	3724(3)	10304(2)	48(1)	1
C3	9171(3)	3989(3)	9649(2)	48(1)	1
C4	6091(3)	4413(3)	9089(3)	51(1)	1
C5	4493(4)	4812(5)	8913(4)	86(2)	1
C6	5612(5)	5765(4)	8612(3)	77(2)	1
C7	4720(5)	5565(5)	8643(3)	85(2)	1
C8	5179(4)	4228(3)	9135(3)	67(2)	1
C9	6302(4)	5199(3)	8834(3)	62(1)	1
C10	6529(3)	2782(3)	9769(3)	53(1)	1
C11	5721(4)	2681(3)	10370(3)	71(2)	1
C12	5319(5)	1977(4)	10702(4)	96(2)	1
C13	5736(6)	1350(4)	10464(4)	102(2)	1
C14	6545(5)	1430(4)	9887(4)	85(2)	1
C15	6926(4)	2146(3)	9530(3)	61(1)	1
C16	9978(3)	2638(3)	9148(3)	49(1)	1
C17	10611(4)	2429(3)	9614(3)	70(2)	1
C18	10938(5)	1662(4)	9867(4)	97(2)	1
C19	10639(6)	1111(4)	9659(4)	108(2)	1
C20	10000(5)	1302(3)	9194(4)	89(2)	1
C22	10462(3)	4248(3)	8274(3)	46(1)	1
C21	9676(4)	2055(3)	8940(3)	64(1)	1
C23	11404(4)	4074(4)	8343(3)	74(2)	1
C24	12100(5)	4613(5)	7957(4)	90(2)	1
C25	11882(5)	5308(5)	7494(4)	86(2)	1
C26	10947(5)	5494(4)	7433(3)	88(2)	1
C27	10234(4)	4956(3)	7827(3)	71(2)	1
C28	8196(5)	2429(3)	12289(3)	74(2)	1
C29	7650(6)	2558(4)	12954(4)	102(2)	1
C30	8051(10)	2510(6)	13532(5)	138(4)	1
C31	9017(9)	2332(6)	13469(6)	157(5)	1
C32	9588(8)	2224(5)	12813(6)	137(3)	1
C33	9181(6)	2269(4)	12220(4)	100(2)	1
C34	7558(5)	1434(3)	11683(3)	75(2)	1
C35	6693(6)	1066(5)	12044(5)	129(3)	1
C36	6667(10)	285(6)	12122(8)	187(6)	1
C37	7427(13)	−134(6)	11872(9)	196(7)	1
C38	8237(10)	201(6)	11542(8)	188(5)	1
C39	8329(7)	1007(4)	11427(6)	142(3)	1
C40	8992(3)	3691(3)	6568(3)	43(1)	1
C41	9316(3)	3562(2)	7220(2)	39(1)	1
C42	10274(3)	3304(3)	7168(3)	49(1)	1
C43	10881(3)	3193(3)	6517(3)	56(1)	1
C44	10505(4)	3350(3)	5892(3)	62(1)	1
C45	9560(3)	3600(3)	5889(3)	53(1)	1
C46	11936(4)	2916(5)	6501(3)	90(2)	1
C47	12482(8)	2801(6)	5804(6)	188(4)	1
C48	12507(6)	3670(6)	6397(6)	163(4)	1
C49	12093(5)	2419(5)	7220(4)	133(3)	1
C50	9154(4)	3754(4)	5193(3)	75(2)	1
C51	9961(5)	3630(5)	4524(3)	129(3)	1
C52	8753(5)	4593(4)	4944(3)	102(2)	1

C53	8363(5)	3187(4)	5361(4)	108(2)	1
C54	6715(3)	5250(3)	6973(2)	46(1)	1
C55	6102(3)	5741(3)	6559(3)	51(1)	1
C56	6218(4)	6523(3)	6401(3)	62(1)	1
C57	6915(4)	6833(3)	6599(3)	64(1)	1
C58	7539(4)	6317(3)	6954(3)	61(1)	1
C59	7449(3)	5527(3)	7144(3)	55(1)	1
C60	5341(4)	5437(3)	6301(3)	62(1)	1
C61	4819(5)	6104(4)	5801(4)	104(2)	1
C62	4593(4)	5004(4)	6961(3)	84(2)	1
C63	5840(4)	4919(4)	5821(3)	78(2)	1
C64	6928(6)	7695(3)	6476(4)	88(2)	1
C65	7873(8)	7918(5)	6534(7)	186(4)	1
C66	6589(9)	8170(6)	5782(6)	184(4)	1
C67	6239(8)	7900(4)	7121(5)	185(5)	1
C68	6822(4)	2309(3)	7731(3)	56(1)	1
C69	6033(4)	1826(3)	8012(3)	62(1)	1
C70	6278(4)	1036(3)	8194(3)	71(2)	1
C71	7215(5)	714(3)	8123(3)	72(2)	1
C72	7962(4)	1221(3)	7831(3)	71(2)	1
C73	7763(4)	2015(3)	7635(3)	61(1)	1
C74	7398(6)	−175(3)	8363(4)	93(2)	1
C75	6929(6)	−507(4)	9214(5)	121(3)	1
C76	6902(7)	−520(4)	7946(5)	153(4)	1
C77	8475(6)	−406(4)	8244(5)	128(3)	1
C78	4982(4)	2141(4)	8097(4)	82(2)	1
C79	4843(5)	2641(4)	7294(5)	118(3)	1
C80	4731(4)	2639(4)	8616(4)	112(3)	1
C81	4285(4)	1483(4)	8391(5)	124(3)	1
C82	8321(4)	4145(3)	10871(3)	61(1)	1
C83	8349(3)	2843(3)	10669(3)	51(1)	1
P5	11972(2)	3269(1)	10814(1)	103(1)	1
F1	10984(4)	3565(4)	10566(4)	138(4)	0.626(11)
F2	12368(4)	2959(6)	10090(4)	150(4)	0.626(11)
F3	11575(4)	3546(6)	11540(4)	201(6)	0.626(11)
F4	12400(6)	4080(3)	10335(5)	177(5)	0.626(11)
F5	11531(6)	2438(3)	11289(5)	190(5)	0.626(11)
F6	12966(4)	2962(5)	11054(4)	178(5)	0.626(11)
F1'	11755(7)	4098(5)	10964(10)	135(7)	0.374(11)
F2'	12054(9)	3682(9)	9936(3)	183(9)	0.374(11)
F3'	11864(10)	2867(9)	11695(3)	279(14)	0.374(11)
F4'	13088(3)	3368(7)	10693(7)	157(7)	0.374(11)
F5'	10836(3)	3193(7)	10941(7)	148(7)	0.374(11)
F6'	12190(8)	2454(5)	10668(10)	162(7)	0.374(11)

Table 3. Bond lengths [Å] and angles [°].

Pd1–C41	2.118(4)
Pd1–P4	2.2594(11)
Pd1–P2	2.3233(12)
Pd1–P1	2.3772(12)
P1–C10	1.809(5)
P1–C4	1.810(5)
P1–C1	1.842(4)
P2–C16	1.809(5)
P2–C22	1.815(5)
P2–C3	1.840(4)
P3–O1	1.474(4)
P3–C34	1.785(6)
P3–C28	1.793(6)
P3–C83	1.822(5)
P4–O3	1.574(3)
P4–O4	1.588(3)
P4–O2	1.591(3)
O4–C68	1.409(5)
O2–C40	1.412(5)
O3–C54	1.416(5)
C1–C2	1.529(6)
C2–C3	1.533(6)
C2–C83	1.536(6)
C2–C82	1.538(6)
C4–C8	1.370(6)
C4–C9	1.404(7)
C5–C7	1.356(9)
C5–C8	1.396(8)
C6–C7	1.358(8)
C6–C9	1.381(7)
C10–C15	1.384(6)
C10–C11	1.389(7)
C11–C12	1.366(8)
C12–C13	1.376(9)
C13–C14	1.366(8)
C14–C15	1.375(7)
C16–C17	1.382(6)
C16–C21	1.403(6)
C17–C18	1.390(8)
C18–C19	1.349(9)
C19–C20	1.387(8)
C20–C21	1.369(7)
C22–C27	1.360(7)
C22–C23	1.381(6)
C23–C24	1.383(8)
C24–C25	1.351(9)
C25–C26	1.369(8)
C26–C27	1.400(8)
C28–C33	1.387(8)
C28–C29	1.390(8)
C29–C30	1.360(11)
C30–C31	1.366(8)
C31–C32	1.371(8)
C32–C33	1.394(9)
C34–C39	1.347(9)
C34–C35	1.392(9)
C35–C36	1.389(12)
C36–C37	1.322(16)
C37–C38	1.294(15)

C38–C39	1.435(12)
C40–C41	1.395(6)
C40–C45	1.396(6)
C41–C42	1.384(6)
C42–C43	1.385(6)
C43–C44	1.384(6)
C43–C46	1.529(7)
C44–C45	1.375(6)
C45–C50	1.537(7)
C46–C47	1.430(11)
C46–C49	1.453(9)
C46–C48	1.624(10)
C50–C52	1.534(8)
C50–C53	1.537(8)
C50–C51	1.545(7)
C54–C59	1.381(6)
C54–C55	1.389(6)
C55–C56	1.385(7)
C55–C60	1.540(6)
C56–C57	1.400(7)
C57–C58	1.361(7)
C57–C64	1.516(7)
C58–C59	1.384(6)
C60–C62	1.501(7)
C60–C63	1.517(7)
C60–C61	1.539(7)
C64–C67	1.490(9)
C64–C65	1.509(11)
C64–C66	1.509(11)
C68–C73	1.375(6)
C68–C69	1.409(7)
C69–C70	1.392(7)
C69–C78	1.530(7)
C70–C71	1.387(7)
C71–C72	1.390(7)
C71–C74	1.545(8)
C72–C73	1.386(7)
C74–C76	1.517(9)
C74–C77	1.526(9)
C74–C75	1.550(9)
C78–C80	1.508(8)
C78–C81	1.531(8)
C78–C79	1.576(9)
P5–F4	1.575(3)
P5–F6'	1.580(4)
P5–F3	1.582(3)
P5–F4'	1.583(4)
P5–F1	1.592(3)
P5–F6	1.595(3)
P5–F3'	1.596(4)
P5–F2'	1.599(4)
P5–F5'	1.603(4)
P5–F1'	1.607(4)
P5–F5	1.611(3)
P5–F2	1.612(3)

C41–Pd1–P4	78.88(11)
C41–Pd1–P2	92.79(11)
P4–Pd1–P2	170.93(5)
C41–Pd1–P1	175.55(11)
P4–Pd1–P1	97.91(4)

P2–Pd1–P1	90.59(4)
C10–P1–C4	106.7(2)
C10–P1–C1	105.2(2)
C4–P1–C1	99.6(2)
C10–P1–Pd1	110.95(16)
C4–P1–Pd1	113.00(16)
C1–P1–Pd1	120.08(16)
C16–P2–C22	108.9(2)
C16–P2–C3	106.6(2)
C22–P2–C3	97.2(2)
C16–P2–Pd1	110.89(15)
C22–P2–Pd1	113.65(15)
C3–P2–Pd1	118.56(15)
O1–P3–C34	112.4(3)
O1–P3–C28	112.0(3)
C34–P3–C28	103.4(3)
O1–P3–C83	115.8(2)
C34–P3–C83	104.1(3)
C28–P3–C83	108.1(3)
O3–P4–O4	94.30(16)
O3–P4–O2	100.37(17)
O4–P4–O2	105.83(17)
O3–P4–Pd1	123.97(12)
O4–P4–Pd1	122.81(14)
O2–P4–Pd1	106.50(11)
C68–O4–P4	127.9(3)
C40–O2–P4	116.0(3)
C54–O3–P4	125.6(3)
C2–C1–P1	122.3(3)
C1–C2–C3	110.6(4)
C1–C2–C83	112.0(4)
C3–C2–C83	111.2(4)
C1–C2–C82	107.4(4)
C3–C2–C82	105.2(4)
C83–C2–C82	110.2(4)
C2–C3–P2	122.1(3)
C8–C4–C9	118.3(5)
C8–C4–P1	124.3(4)
C9–C4–P1	117.4(4)
C7–C5–C8	120.7(6)
C7–C6–C9	120.2(6)
C5–C7–C6	120.2(6)
C4–C8–C5	120.1(6)
C6–C9–C4	120.5(5)
C15–C10–C11	118.2(5)
C15–C10–P1	119.7(4)
C11–C10–P1	122.1(4)
C12–C11–C10	120.6(6)
C11–C12–C13	120.2(6)
C14–C13–C12	120.3(6)
C13–C14–C15	119.6(6)
C14–C15–C10	121.1(5)
C17–C16–C21	118.1(5)
C17–C16–P2	123.0(4)
C21–C16–P2	118.8(4)
C16–C17–C18	120.6(5)
C19–C18–C17	120.2(6)
C18–C19–C20	120.6(6)
C21–C20–C19	119.6(6)
C27–C22–C23	118.9(5)
C27–C22–P2	117.8(4)

C23–C22–P2	123.0(4)
C20–C21–C16	120.8(5)
C22–C23–C24	120.2(6)
C25–C24–C23	121.1(6)
C24–C25–C26	119.3(6)
C25–C26–C27	120.1(6)
C22–C27–C26	120.4(5)
C33–C28–C29	117.7(6)
C33–C28–P3	124.5(5)
C29–C28–P3	117.7(6)
C30–C29–C28	121.9(8)
C29–C30–C31	120.1(9)
C30–C31–C32	119.9(10)
C31–C32–C33	120.2(9)
C28–C33–C32	120.1(8)
C39–C34–C35	117.6(7)
C39–C34–P3	124.5(6)
C35–C34–P3	117.9(6)
C36–C35–C34	119.0(9)
C37–C36–C35	123.3(12)
C38–C37–C36	118.3(11)
C37–C38–C39	122.4(12)
C34–C39–C38	119.5(9)
C41–C40–C45	125.2(4)
C41–C40–O2	117.6(4)
C45–C40–O2	117.2(4)
C42–C41–C40	115.2(4)
C42–C41–Pd1	126.3(3)
C40–C41–Pd1	118.1(3)
C41–C42–C43	123.0(4)
C44–C43–C42	117.9(4)
C44–C43–C46	122.0(4)
C42–C43–C46	120.1(4)
C45–C44–C43	123.4(4)
C44–C45–C40	115.3(4)
C44–C45–C50	122.4(4)
C40–C45–C50	122.4(4)
C47–C46–C49	121.7(7)
C47–C46–C43	114.8(6)
C49–C46–C43	114.0(5)
C47–C46–C48	94.3(7)
C49–C46–C48	100.6(6)
C43–C46–C48	106.5(6)
C52–C50–C45	111.1(5)
C52–C50–C53	110.3(5)
C45–C50–C53	109.9(5)
C52–C50–C51	107.1(6)
C45–C50–C51	110.4(4)
C53–C50–C51	107.9(5)
C59–C54–C55	121.9(5)
C59–C54–O3	119.8(4)
C55–C54–O3	118.2(4)
C56–C55–C54	115.0(4)
C56–C55–C60	122.5(4)
C54–C55–C60	122.5(4)
C55–C56–C57	125.1(5)
C58–C57–C56	116.7(5)
C58–C57–C64	121.6(5)
C56–C57–C64	121.6(5)
C57–C58–C59	121.2(5)
C54–C59–C58	120.0(5)

C62–C60–C63	110.2(5)
C62–C60–C61	108.0(5)
C63–C60–C61	106.3(5)
C62–C60–C55	111.4(4)
C63–C60–C55	109.4(4)
C61–C60–C55	111.4(5)
C67–C64–C65	101.3(7)
C67–C64–C66	106.0(7)
C65–C64–C66	115.3(8)
C67–C64–C57	109.2(6)
C65–C64–C57	112.1(6)
C66–C64–C57	112.0(6)
C73–C68–C69	122.0(5)
C73–C68–O4	120.3(4)
C69–C68–O4	117.8(4)
C70–C69–C68	115.1(5)
C70–C69–C78	122.0(5)
C68–C69–C78	122.9(5)
C71–C70–C69	124.8(5)
C70–C71–C72	117.3(5)
C70–C71–C74	120.2(5)
C72–C71–C74	122.5(6)
C73–C72–C71	120.5(5)
C68–C73–C72	120.3(5)
C76–C74–C77	112.1(6)
C76–C74–C71	109.3(6)
C77–C74–C71	111.8(6)
C76–C74–C75	107.1(7)
C77–C74–C75	107.5(6)
C71–C74–C75	108.9(6)
C80–C78–C69	111.3(5)
C80–C78–C81	109.4(6)
C69–C78–C81	111.2(5)
C80–C78–C79	109.3(6)
C69–C78–C79	108.2(5)
C81–C78–C79	107.3(5)
C2–C83–P3	118.4(3)
F4–P5–F6'	130.7(4)
F4–P5–F3	91.92(16)
F6'–P5–F3	134.5(4)
F4–P5–F4'	61.3(4)
F6'–P5–F4'	91.1(2)
F3–P5–F4'	98.8(5)
F4–P5–F1	89.47(16)
F6'–P5–F1	103.1(4)
F3–P5–F1	90.26(17)
F4'–P5–F1	149.5(4)
F4–P5–F6	90.87(16)
F6'–P5–F6	76.0(5)
F3–P5–F6	90.61(15)
F4'–P5–F6	30.6(4)
F1–P5–F6	179.1(2)
F4–P5–F3'	126.7(4)
F6'–P5–F3'	90.67(19)
F3–P5–F3'	45.2(4)
F4'–P5–F3'	91.12(19)
F1–P5–F3'	115.2(4)
F6–P5–F3'	65.3(4)
F4–P5–F2'	53.3(4)
F6'–P5–F2'	90.14(19)
F3–P5–F2'	133.7(4)

5–F2'	90.07(19)
–F2'	63.5(4)
–F2'	116.1(4)
5–F2'	178.6(3)
–F5'	117.4(4)
5–F5'	90.57(19)
–F5'	80.0(4)
5–F5'	178.3(3)
–F5'	29.7(4)
–F5'	150.3(4)
5–F5'	88.92(19)
5–F5'	89.87(18)
–F1'	49.2(4)
5–F1'	179.8(3)
–F1'	45.4(4)
5–F1'	88.65(18)
–F1'	77.1(4)
–F1'	103.8(4)
5–F1'	89.25(19)
5–F1'	89.95(19)
5–F1'	89.66(19)
–F5	178.8(2)
5–F5	48.5(4)
–F5	89.10(16)
5–F5	119.1(4)
–F5	89.90(15)
–F5	89.75(16)
5–F5	54.5(4)
5–F5	125.5(4)
5–F5	62.2(4)
5–F5	131.6(4)
–F2	89.88(16)
–F2	43.7(4)
–F2	178.2(2)
5–F2	81.8(4)
–F2	89.99(15)
–F2	89.13(16)
5–F2	133.2(4)
–F2	47.9(4)
–F2	99.4(4)
–F2	136.4(4)
–F2	89.10(15)

etry transformations used to generate equivalent atoms: