2-Pyridyl substituents enhance the activity of palladium–phospha-adamantane catalysts for the methoxycarbonylation of phenylacetylene†

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The synthesis of a series of CgPAr ligands is reported, where CgP is the 6-phospha-2,4,8-trioxa-1,3,5,7-tetramethyladamant-6-yl moiety and Ar = 2-pyridyl (L2), 3-pyridyl (L3), 2-pyrimidyl (L4), 4-R-2-pyridyl [R = Me (L5a), CF3 (L5b), SiMe3 (L5c)] or 6-R-2-pyridyl [R = Me (L5a), CF3 (L5b), SiMe3 (L5c)]. Testing of these ligands in the Pd-catalysed methoxycarbonylation of phenylacetylene reveals that the activity and branched selectivity of the catalysts derived from these ligands varies as a function of the N-heterocycle, with the catalyst derived from L5a being the most active of those tested. This, together with the poor performance of catalysts derived from L5 supports the hypothesis that the catalysis proceeds by a “proton shuttling” mechanism, an idea that previously had only been applied to arylphosphines. Reaction of [PtCl2(cod)] with L where L = L2 or L4–7 yields a rac/meso mixture of the trans-[PtCl2(L)2] complexes, three of which are structurally characterised. 31P NMR spectroscopy shows that reaction of L3 with [PtCl2(cod)] gives a mixture of mononuclear and binuclear metal complexes in solution. The complex trans-[PdCl2(L2)]4 reacts with AgBF4 to give the [PdCl(L1)(L2)]BF4 (5) with spectroscopic and structural characterisation confirming the presence of a P,N-chelate. 1H and 31P NMR evidence supports the assignment of a pyridyl-protonated species being formed upon treatment of 4 with TsOH·H2O in CD2Cl2; both the protonated species and chelate 5 are observed when the reaction is carried out in MeOH.

Introduction

The palladium-catalysed methoxycarbonylation of alkynes (Scheme 1) is an atom-efficient way of producing branched or linear α,β-unsaturated esters from readily available feedstocks.1,2 The methoxycarbonylation of propyne (Scheme 1, R = Me) has been extensively studied owing to the industrial interest in the branched product, methyl methacrylate (MMA) which is a precursor to poly(methyl methacrylate).3 The methoxycarbonylation of phenylacetylene (Scheme 1, R = Ph) produces methyl atropate (branched product), a precursor to ibuprofen4 or methyl cinnamate (linear product), which has applications in the perfume and flavouring industries.4

The activity, selectivity and stability of the palladium catalyst for methoxycarbonylation depend critically on the ligand. Drent et al. reported that changing the ligand from PPh3 to Ph3P(2-py) (L1) led to an increase in rate of three orders of magnitude for propyne and an increase in branched selectivity from 89% to 99%.5 It was postulated that a “non-classical” carbomethoxy mechanism involving P,N-chelates was in operation and the greater catalyst activity was a result of the Ph3P(2-py) acting as a “proton messenger”,5 by bringing the proton into close proximity to the metal and thereby promoting the protonolysis of the proposed vinyl-palladium intermediate as shown in Scheme 2.

Recently, Bühl et al. reported a computational study of several possible pathways for methoxycarbonylation.5 Drent’s original mechanism was challenged, as it was found that the postulated, selectivity-determining transition state would

Scheme 1

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†Electronic supplementary information (ESI) available: Crystal structures of ligands L2–7 and crystal structure and refinement details. CCDC 1497885–1497898. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/c6dt03983a
favour the formation of linear product (methyl crotonate) over the branched product (MMA). Instead, an alternative cycle involving labile P,N-chelates was proposed which proceeded by an in situ base mechanism (Scheme 3) closely related to that described by Scrivanti et al. This was suggested to be the most plausible mechanism due to it having surmountable barriers congruent with the high turnover and selectivity observed experimentally with L1. Common to the Drent and Bühl mechanisms (Schemes 2 and 3) is the chelation of the P,N ligand which acts to stabilise the catalyst. Catalysts derived from Ph2P(2-py) have been shown to be excellent for phenylacetylene methoxycarbonylation (Scheme 1, R = Ph).

It has also been observed that substituents on the 2-pyridyl ring have a pronounced effect upon the performance of the catalyst; moreover Ph2P(3-py) and Ph2P(4-py) give catalysts of much lower activity. Palladium complexes of other monophosphines with the potential to form heterodonor P,L-chelates (e.g. pyrimidylphosphines, iminophosphines, phosphinoquinilines, furylphosphines and so called TROPPs) have been shown to be efficient methoxycarbonylation catalysts. It is notable that in all of these ligands an Ar2P moiety is present.

Ligands incorporating the 6-phospha-2,4,8-trioxa-1,3,5,7-tetramethyladamant-6-yl (CgP) moiety are effective for a range of Pd-catalysed carbonylation reactions. CgPR and tBu2PR are comparable in terms of bulk but very different in σ/π-bonding characteristics: the donor properties of CgPR are comparable to a (PhO)2PR. It was therefore of interest to investigate CgP(2-py) (L2) and its derivatives as ligands for Pd-catalysed methoxycarbonylation of phenylacetylene. We show here that the Pd–L2 catalysts are active and that 4- and 6-substituents on the 2-pyridyl affect the performance of the catalyst. The platinum and palladium coordination chemistry of these ligands has been explored which has given some insight into the function of L2 and related ligands.

Results and discussion

Ligand synthesis

The synthesis of CgP(2-py) (L2) has previously been reported via a Pd-catalysed P-arylation of CgPH and we have extended the route to the preparation of cage phosphines containing 3-pyridyl (L3), 2-pyrimidyl (L4), 4-substituted-2-pyridyl (L5–7a) and 6-substituted-2-pyridyl (L5–7b) (Scheme 4). These air-stable ligands were purified by column chromatography and have been fully characterised. Crystals of all of the ligands L2–7 suitable for X-ray crystallography have been obtained. The structures are very similar to each other and so only L2, as a representative structure, is shown in Fig. 1 along with its main metrical parameters; the structures of L3–7 are given in the ESI.

Methoxycarbonylation catalysis

In order to draw comparisons in performance among the ligands, the methoxycarbonylation of phenylacetylene (eqn (1)) has been carried out in the presence of L1–7, PPh3 and CgPPh under the same reaction conditions and the results are presented in Table 1.
Under the conditions we used for the catalysis, the PPh₃ catalyst produced low and inconsistent conversions (entry 1) and at the end of the runs, copious amounts of black deposit, presumably metallic palladium, was observed indicating that the catalyst was not stable. As previously reported, the very high activity of the catalyst derived from L₄ (entry 3) contrasts sharply with that of the isosteric PPh₃ analogue (entry 1). The CgPPh is superior to PPh₃ in producing a moderately active catalyst (entry 2) that shows no evidence of decomposition to metallic Pd during the catalytic runs.

The results for the catalysts derived from L₅ and L₆ show that substituents Me, CF₃ and SiMe₃ at the 4- and 6-positions in the 2-pyridyl ring can, in some cases, have a significant effect on the conversion compared to the unsubstituted L₂. However, there appears to be no consistent trends associated with the stereoelectronic effect of the substituents. Relative to L₂: (1) the 4-Me ligand L₅a (entry 5) gives a significantly lower conversion while the 6-Me ligand L₅b (entry 6) gives a significantly higher conversion; (2) the 4-CF₃ and 4-SiMe₃ ligands, L₆a (entry 7) and L₆b (entry 9), perform similarly to L₂ while the 6-CF₃ and 6-SiMe₃ ligands, L₆b (entry 8) and L₆b (entry 10), produce catalysts of lower activity than L₂.

In terms of branched selectivity, there is some evidence that the 6-substituted 2-pyridyl ligands L₅-₇b give more branched-selective catalysts than their 4-substituted isomers L₅-₇a (entries 5–10). Others have reported similar observations with 4- and 6-substituted pyridyl derivatives of L₄ that is, greater branched selectivity was obtained with 6-substituted than with 4-substituted pyridyl ligands.

In order to elucidate the function of the 2-pyridyl in the Pd-catalysis, the coordination chemistry of L₄ with Pt and Pd has been investigated.

### Coordination chemistry

Ligands L₂–₇ have been reacted with [PtCl₂(cod)] (cod = 1,5-cyclooctadiene) in CH₂Cl₂. With the exception of the reaction with L₁ (see below), products of the type trans- [PtCl₂(L₁)] (1a–h) were obtained (Scheme 5) which have been fully characterised.

![Scheme 4](image-url)
The $^{31}$P NMR spectra of the products in each case showed two closely spaced singlets with $^{195}$Pt satellites ($^{1}J_{P,Pt}$ values are typical of trans-[PtCl$_2$(PR$_3$)$_2$] complexes) consistent with the presence of rac and meso diastereomers resulting from the chirality of the cage ligands.

Crystals suitable for X-ray crystallography of 1c, 1d, 1e and 1g (meso isomers in each case) were grown by slow diffusion of hexane into a CH$_2$Cl$_2$ solution of a rac/meso mixture of the corresponding complex. As shown in Fig. 2–5, in each case, the ligands adopt an anti conformation, with the C(pyridyl)–P–P–C(pyridyl) torsion angle of 180°.

The reaction of [PtCl$_2$(cod)] with the 3-pyridyl ligand gave different results from those for all of the 2-pyridyl ligands. The $^{31}$P NMR spectrum of the products of the reaction of [PtCl$_2$(cod)] with 2 equiv. of the 3-pyridyl ligand showed four signals with $^{195}$Pt satellites, as well as free ligand ($\delta_P$ = 29.5 ppm). Two of the signals were assigned to rac/meso-[PtCl$_2$(L$_3$)$_2$] (1h) because of the similarity of their $^{31}$P NMR data ($\delta_P$ = 2.6 ppm, $^{1}J_{P,Pt}$ = 2703 Hz; $\delta_P$ = 2.8 ppm, $^{1}J_{P,Pt}$ = 2710 Hz) to those of the analogues 1a–h. The remaining two signals were assigned to binuclear complexes of the type [Pt$_2$Cl$_2$(L$_3$)$_2$(μ-Cl)$_2$].

Fig. 3 Crystal structure of meso-1d, showing the anti–trans conformation adopted by the ligands. Hydrogen atoms omitted for clarity. Atoms suffixed with a dash (‘) are related by symmetry operation (–x, 1–y, –z). Thermal ellipsoids at 50% probability. Selected bond lengths (Å) and angles (*): Pt1–Cl1 2.3119(6), Pt1–P1 2.3198(6), P1–C1 1.883(3), P1–C4 1.878(3), P1–Cl1 1.845(3), C1–P1–C4 93.99(11), C1–P1–C11 103.98(12), C4–P1–C11 111.54(12).

on the basis of their large $^{1}J_{P,Pt}$ values ($\delta_P$ 8.3 ppm, $^{1}J_{P,Pt}$ = 4592 Hz; $\delta_P$ 7.9 ppm $^{1}J_{P,Pt}$ = 4608 Hz). Two types of isomerism (syn/anti and rac/meso) would be expected for [Pt$_2$Cl$_2$(L$_3$)$_2$(μ-Cl)$_2$]; in view of the 0.4 ppm difference in their $\delta_P$ values, we tentatively assign the two observed $^{31}$P NMR signals to syn- and anti-2 (Scheme 6) with the signals expected for the rac and meso isomers unresolved. Mixtures of mononuclear and binuclear products were also reported in the reaction of [PtCl$_2$(cod)] with 2 equiv. CgPPh$_3$ and so the observation of exclusive formation of mononuclear complexes 1a–h appears to be an effect of the 2-pyridyl group. It is tempting to associate this with weak Pt⋯N interactions stabilising the mononuclear complexes.

Fig. 4 Crystal structure of meso-1e, showing the anti–trans conformation adopted by the ligands. Hydrogen atoms omitted for clarity. Atoms suffixed with a dash (‘) are related by symmetry operation (–x, 1–y, –z). Thermal ellipsoids at 50% probability. Selected bond lengths (Å) and angles (*): Pt1–Cl1 2.3056(5), Pt1–P1 2.3227(5), P1–C1 1.877(2), P1–C4 1.886(3), P1–Cl1 1.842(2), C1–P1–C4 94.43(10), C1–P1–C11 105.04(13), C4–P1–C11 109.69(10).
The ability of 2-pyridylphosphines to switch between P-monodentate and P,N-bidentate coordination has been invoked as part of the explanation for the high activity of Pd-complexes of 2-pyridylphosphines in methoxycarbonylation.3,5,6 It was therefore of interest to investigate if 2-pyridylphosphine L2 could form 4-membered P,N-chelates. Treatment of the trans complex 1a with 1 equiv. of AgBF4 gave a precipitate of AgCl and a solution whose 31P{1H} NMR spectrum was consistent with the formation of the monochelate 3[BF4] (Scheme 7). Two doublets were observed at −48.1 ppm (1J_P,Pt = 2728 Hz) and +0.8 ppm (1J_P,Pt = 3514 Hz) with a small 2J_P,P of 11 Hz typical of cis coordinated phosphines. The signal at −48.1 ppm is assigned to the P,N-chelate since its high field shift is characteristic of a 4-membered chelate.16 The lower value of 1J_P,Pt for the chelate-P is consistent with the ring strain being relieved by lengthened Pt–P bonds; the crystal structure of the Pd analogue 5[BF4] (see below) supports this inference.

In a similar manner to that described above for the Pt analogues, reaction of [PdCl2(cod)] with 2 equiv. of L2 yielded trans-[PdCl2(L2)2] (4) which has been fully characterised. Treatment of 4 with 1 equiv. of AgBF4 gave a product assigned the structure 5[BF4], the Pd analogue of 3[BF4] (Scheme 8). Crystals of 5[BF4] suitable for X-ray crystallography were obtained and its crystal structure determined (Fig. 6) which confirmed the cis orientation of the two P-donors. The chelate ring strain is apparent from the acute P–Pd–N angle of 69.0°. The Pd–P length within the chelate is longer (by ca. 0.02 Å) although in the solid state at least, no such interactions were detected in complexes 1c–e and 1g (see Fig. 2–5).

The ability of 2-pyridyldiphosphines to switch between P-monodentate and P,N-bidentate coordination has been invoked as part of the explanation for the high activity of Pd-complexes of 2-pyridyldiphosphines in methoxycarbonylation.4,5,6 It was therefore of interest to investigate if 2-pyridylphosphine L2 could form 4-membered P,N-chelates. Treatment of the trans complex 1a with 1 equiv. of AgBF4 gave a precipitate of AgCl and a solution whose 31P{1H} NMR spectrum was consistent with the formation of the monochelate 3[BF4] (Scheme 7). Two doublets were observed at −48.1 ppm (1J_P,Pt = 2728 Hz) and +0.8 ppm (1J_P,Pt = 3514 Hz) with a small 2J_P,P of 11 Hz typical of cis coordinated phosphines. The signal at −48.1 ppm is assigned to the P,N-chelate since its high field shift is characteristic of a 4-membered chelate.16 The lower value of 1J_P,Pt for the chelate-P is consistent with the ring strain being relieved by lengthened Pt–P bonds; the crystal structure of the Pd analogue 5[BF4] (see below) supports this inference.

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than that for the monodentate ligand perhaps reflecting the ring strain.

The $^{31}P\{^1H\}$ NMR spectrum of $5[BF_4]$ in CHCl$_3$CHCl$_2$ showed a slightly broadened ($w_{1/2} \sim 8$ Hz) signal at 28.8 ppm, corresponding to the monodentate ligand, and a sharp doublet at $-42.7$ ppm ($J_{P,P} = 3.2$ Hz), assigned to the P,N-chelate. The signals remain distinct but broaden as the temperature is raised (e.g. $w_{1/2} \sim 70$ Hz at 100 °C in CHCl$_3$CHCl$_2$) indicating that cation 5 is fluxional, which is associated with intramolecular interchange of chelating and non-chelating P,N ligands. Iggo et al. have shown that the complex [PdCl2{k1-P2P(2-py)}][{k2-P2P(2-py)}]BF$_4$ (an analogue of $5[BF_4]$) is fluxional but with a coalescence temperature for the $^{31}P$ NMR signals of $-30$ °C which is at least 150 °C lower than for cation 5. The high barrier to exchange in 5 can be rationalised in terms of steric hindrance to Pd-P bond rotation which may be required in order for the pyridyl-nitrogen in the $k^1$-L$_2$ to coordinate. Energy barriers to Pd-N coordination at the pyridyl-nitrogen have been shown to be of the order of 50 kJ mol$^{-1}$.

Complex 4 is only sparingly soluble in CD$_2$Cl$_2$ but addition of 1.1 equiv. of TsOH-H$_2$O to a suspension of 4 in CD$_2$Cl$_2$ gave a homogenous yellow solution. The $^{31}P$ NMR spectrum showed two broad peaks at 6.0 and 3.7 ppm ($w_{1/2} \sim 57$ Hz and 53 Hz respectively), which are tentatively assigned to diastereoisomers of protonated species such as 6 (Scheme 9) with rapid proton exchange rendering the $^{31}P$ NMR signals equivalent on the NMR timescale. In the $^1H$ NMR spectrum of 6 a broad signal centred at 6.55 ppm is assigned to the exchanging N-H. When a suspension of 4 in MeOH was treated with TsOH, the $^{31}P$ NMR spectrum of the resulting solution displayed two broad signals at 6.3 and 4.5 ppm (assigned to 6) but in addition, two signals at 28.8 and $-42.2$ ppm are present, suggesting that the P,N-chelate $5[OTs]$ is also generated (Scheme 9).

The Pd and Pt coordination chemistry of L$_2$ has shown that the ligand can be monodentate ($k^1$) or chelating ($k^2$) and the pyridyl-N can be protonated by TsOH. These properties are essential for the catalyst to be able to function in a manner similar to L$_4$ shown in Schemes 1 and 2. Tellingly, the $^{31}P\{^1H\}$ NMR spectrum of the mixture obtained after catalysis runs involving Pd and L$_4$ showed, amongst other peaks, a prominent signal at $-37.8$ ppm, reminiscent of the peak observed at $-42.1$ ppm for the cation 5, suggesting that a four-membered Pd chelate is present.

Conclusions

A series of substituted pyridyl-functionalised phospha-adamantyl ligands L$_{2-7}$ have been made and fully characterised. It was found that, in some cases, substituents on the pyridyl ring had a marked effect on the rate of Pd-catalysed methoxycarbonylation of phenylacetylene. The 6-methyl substituted ligand L$_{5b}$ showed good activity and selectivity for the branched product albeit lower than that of the well-known Ph$_2$P(2-py) (L$_1$). The catalytic performance is a function of the substituents on the pyridine consistent with the idea that a mechanism involving P,N-chelation and “proton shuttling” may be operating.

The Pt and Pd coordination chemistry of L$_{2-7}$ has been probed and the ability of the ligands to form P,N-chelates has been established in solution from the characteristic $^{31}P$ NMR spectra and in the solid state by the crystal structure of a palladium complex containing L$_2$ ligands bound in a $k^1$ and $k^2$-mode. Moreover protonation of the pyridyl-N in a Pd-L$_2$ complex has been observed in solution. In contrast to the CgP(2-py) ligands, the CgP(3-py) ligand L$_3$ gives binuclear Pt complexes in a similar fashion to the CgPPH.

The methoxycarbonylation activity with catalysts derived from CgP(2-py) and its derivatives demonstrates that the 2-pyridyl effect is not restricted to Ph$_2$P(2-py) and its derivatives. The CgP and Ph$_2$P moieties have very different stereoelectronic effects and therefore the results presented hold out the prospect that other R$_2$P(2-py) ligands may be useful for alkyne methoxycarbonylation catalysis.

Experimental

General procedures

All reactions were carried out under an atmosphere of dry nitrogen, unless otherwise stated, using standard Schlenk line techniques and oven dried (200 °C) glassware. CH$_2$Cl$_2$ and hexane were collected from a Grubbs type solvent purification system, and deoxygenated by bubbling with N$_2$ for 30 minutes. Xylene and CD$_2$Cl$_2$ were dried over activated 4 Å molecular sieves for 72 hours and deoxygenated by successive freeze–pump–thaw cycles. MeOH was purchased as anhydrous, stored over 3 Å molecular sieves and deoxygenated by bubbling with N$_2$ for 30 minutes. Other commercial reagents were used as supplied unless otherwise stated. [PtCl$_3$(cod)]$_{19}$, [PdCl$_2$(cod)]$_{20}$, 1,3,5,7-tetramethyl-4,6,8-trioxo-2-phospha-adamantane (CgPH)$_{21}$ CgPPH$_{14}$, Ph$_2$P(2-py)$_{22}$ (L$_4$) 2-bromo-4-(trimethylsilyl)pyridine$_{23}$ and 2-bromo-6-(trimethylsilyl)pyridine$_{24}$ were synthesised accord-
CgP(2-pyrm) (L₄). Purification by flash column chromatography (20% EtOAc/hexane) yielded the product as a white solid (0.679 g, 80%). Crystals suitable for X-ray diffraction were grown by slow evaporation of a CH₂Cl₂ solution of the product. 1H NMR (500 MHz, CDCl₃): δ_H = 8.69 (d, J_H-H = 4.9 Hz, 2H, ArH (H-4 and H-6)), 7.13 (t, J_H-H = 4.9 Hz, 1H, ArH (H-5)), 2.19 (d, J_H-H = 13.3 Hz, 1H, CgP CH₂), 2.14 (dd, J_H-H = 13.1 Hz, J_H-P = 6.7 Hz, 1H, CgP CH₂), 1.92 (dd, J_H-H = 25.2 Hz, J_H-H = 13.3 Hz, 1H, CgP CH₂), 1.78 (d, J_H-P = 12.0 Hz, 3H, CgP CH₃), 1.72 (d, J_H-H = 12.7 Hz, 3H, CgP CH₃), 1.66 (dd, J_H-H = 13.3 Hz, J_H-P = 4.7 Hz, 1H, CgP CH₃), 1.42 (s, 3H, CgP CH₃), 1.27 (s, 3H, CgP CH₃). 13C{¹H} NMR (162 MHz, CDCl₃): δ_C = 174.8 (J_c-c = 9.7 Hz, ArC (C-2)), 156.1 (J_c-c = 5.0 Hz, ArC (C-4 and C-6)), 119.3 (s, ArC (C-5)), 96.6 (s, CgP quatr. C), 96.4 (s, CgP quatr. C), 74.4 (J_c-c = 24.8 Hz, CgP quatr. C), 73.9 (J_c-c = 6.9 Hz, ArC (C-4)), 45.6 (J_c-c = 17.1 Hz, CgP CH₂), 38.5 (J_c-c = 1.9 Hz, CgP CH₂), 28.7 (J_c-c = 19.3 Hz, CgP CH₂), 28.1 (s, CgP CH₂), 27.9 (s, CgP CH₂), 27.6 (J_c-c = 10.2 Hz, CgP CH₂), 24.5 (s, CgP quatr. C). m/z calc. for C₁₄H₁₉N₂O₃P [M⁺] = 294.1133; obs. = 294.1137. Elem. Anal. found (calc. for C₁₄H₁₉N₂O₃P): C, 57.10 (57.14); H, 6.53 (6.51); N, 9.33 (9.52).

CgP(4-Me-2-py) (L₅a). Purification by flash column chromatography (40% diethyl ether/hexane) yielded the product as a white solid (0.343 g, 74%). Crystals suitable for X-ray diffraction were grown by slow diffusion of hexane into a CH₂Cl₂ solution of the product. 1H NMR (400 MHz, CDCl₃): δ_H = 8.53 (d, J_H-H = 5.0 Hz, 1H, ArH (H-6)), 7.77 (s, 1H, ArH (H-3)), 7.02 (d, J_H-H = 5.0 Hz, 1H, ArH (H-5)), 3.34 (s, 3H, Ar-Ch₂), 3.07 (dd, J_H-H = 13.2 Hz, J_H-P = 6.7 Hz, 1H, CgP CH₂), 1.91 (dd, J_H-H = 23.4 Hz, J_H-H = 13.3 Hz, 1H, CgP CH₂), 1.83 (d, J_H-H = 13.2 Hz, 1H, CgP CH₂), 1.57 (d, J_H-H = 12.4 Hz, 3H, CgP CH₃), 1.50 (dd, J_H-H = 13.3 Hz, J_H-P = 4.1 Hz, 1H, CgP CH₃), 1.41 (s, 3H, CgP CH₃), 1.40 (d, J_H-H = 12.4 Hz, 3H, CgP CH₃), 1.37 (s, 3H, CgP CH₂). 13C{¹H} NMR (101 MHz, CDCl₃): δ_C = 160.4 (J_c-c = 12.7 Hz, ArC (C-2)), 149.9 (d, J_c-c = 14.2 Hz, ArC (C-4)), 146.5 (d, J_c-c = 1.8 Hz, ArC (C-4)), 130.2 (d, J_c-c = 10.5 Hz, ArC (C-3)), 124.0 (s, ArC (C-5)), 96.9 (s, CgP quatr. C), 96.3 (s, CgP quatr. C), 73.5 (d, J_c-c = 9.9 Hz, CgP quatr. C), 73.1 (d, J_c-c = 22.9 Hz, CgP quatr. C), 45.2 (d, J_c-c = 16.7 Hz, CgP CH₂), 37.5 (d, J_c-c = 2.1 Hz, CgP CH₂), 28.2 (s, CgP CH₂), 28.0 (s, CgP CH₂), 27.9 (d, J_c-c = 20.6 Hz, CgP CH₃), 27.3 (d, J_c-c = 11.7 Hz, CgP CH₃), 21.4 (s, Ar-Ch₂). 31P{¹H} NMR (162 MHz, CDCl₃): δ_P = 24.5 (s, CgP). HRMS (El): m/z calc. for C₁₆H₂₂NO₃P₂ [M⁺] = 307.1337; obs. = 307.1331. Elem. Anal. found (calc. for C₁₆H₂₂NO₃P₂): C, 62.62 (62.53); H, 7.25 (7.22); N, 4.54 (4.56).

CgP(6-Me-2-py) (L₅b). Purification by flash column chromatography (5% EtOAc/hexane) yielded the product as a white solid (0.578 g, 82%). Crystals suitable for X-ray diffraction were grown by slow evaporation of a CHCl₃ solution of the product. 1H NMR (400 MHz, CDCl₃): δ_H = 7.78 (d, J_H-H = 7.7 Hz, 1H, ArH (H-3)), 7.51 (t, J_H-H = 7.7 Hz, 1H, ArH (H-4)), 7.06 (d, J_H-H = 8.2 Hz, 1H, ArH (H-5)), 2.54 (s, 3H, Ar-Ch₂), 2.07 (dd, J_H-H = 13.2 Hz, J_H-P = 6.7 Hz, 1H, CgP CH₂), 1.89 (dd, J_H-H = 23.1 Hz, J_H-P = 13.2 Hz, 1H, CgP CH₂), 1.82 (d, J_H-H = 13.3 Hz, 1H, CgP CH₃), 1.48 (dd, J_H-H = 13.3 Hz, J_H-P = 4.1 Hz, 1H, CgP CH₃), 1.55
Purification by flash column chromatography (10% EtOAc/hexane) yielded the product as a white solid (0.390 g, 56%). Crystals suitable for X-ray diffraction were grown by slow evaporation of a CH2Cl2 solution of the product. 1H NMR (500 MHz, CDCl3): δH 8.64 (d, JH-H = 4.7 Hz, 1H, ArH (H-3)), 8.11 (br s, 1H, ArH (H-6)), 7.30 (d, JH-H = 4.7 Hz, 1H, ArH (H-5)), 2.10 (dd, JH-H = 13.3 Hz, 3H, JH-P = 6.6 Hz, 1H, CgP CH3), 1.92 (dd, JH-H = 23.4 Hz, 3JH-C = 13.2 Hz, 1H, ArH (C-6)), 1.80 (d, JH-H = 13.3 Hz, 1H, CgP CH3), 1.57 (d, JH-H = 12.4 Hz, 3H, CgP CH3), 1.51 (dd, JH-H = 13.3 Hz, 3H, JH-P = 4.1 Hz, 1H, CgP CH3), 1.42 (s, 3H, CgP CH3), 1.41 (d, JH-H = 12.6 Hz, 3H, CgP CH3), 1.37 (s, 3H, CgP CH3), 0.32 (s, 9H, Si(CH3)3). 13C{1H} NMR (126 MHz, CDCl3): δC 159.6 (d, JH-C = 13.5 Hz, ArC (C-2)), 130.4 (d, JH-C = 13.4 Hz, ArC (C-3)), 133.9 (d, JH-C = 9.1 Hz, ArC (C-6)), 132.7 (s, ArC (C-5)), 96.9 (s, CgP CH3), 73.5 (d, JH-C = 9.7 Hz, CgP CH3), 73.1 (d, JH-C = 22.7 Hz, CgP CH3), 45.2 (d, JH-C = 16.7 Hz, CgP CH3), 37.5 (d, JH-C = 2.1 Hz, CgP CH3), 28.2–27.8 (m, CgP CH3), 27.3 (d, JH-C = 11.6 Hz, CgP CH3), 1.6 (s, Si(CH3)3). 19F NMR (377 MHz, CDCl3): δF -64.8 (s, Ar-CF3). 31P{1H} NMR (162 MHz, CDCl3): δP = -24.2 (s, CgP CH3). HRMS (ESI): m/z calc. for C16H16F3NO3P [M + H]+ = 366.1678; obs. = 366.1678. Elem. Anal. found (calc. for C16H16F3NO3P): C 62.53 (62.53); H, 5.38 (5.30); N, 3.75 (3.88).
heating in MeOH (ca. 0.5 cm³) with TsOH·H₂O (2 equiv.) and Pd(OAc)₂ (0.1 equiv.) for 24 h and no decomposition was observed.)

\[ \text{[PtbCl}_{4}\text{]}(1\text{a}) \]

A solution of \( L_2 \) (0.157 g, 0.537 mmol) in CH₂Cl₂ (2 cm³) was added to a solution of \( \text{[PtbCl}_{2}\text{(cod)}] \) (0.100 g, 0.267 mmol) in CH₂Cl₂ (2 cm³) and stirred for 24 hours. In air, the product was then precipitated in hexane (ca. 25 cm³). After the mixture was allowed to settle, the supernatant was removed using a pipette and the residual solvent removed in vacuo to give the product as a pale yellow solid (0.022 g, 8%). Crystals suitable for X-ray diffraction were grown by slow diffusion of hexane into a CH₂Cl₂ solution of the product. \( \text{rac:meso} \) compounds observed in 3:2 ratio.

\[ \text{[PtbCl}_{2}\text{(L}_1\text{)}\text{]}(1\text{b}) \]

A solution of \( L_4 \) (0.033 g, 0.110 mmol) in CH₂Cl₂ (1 cm³) was added to a solution of \([\text{PtbCl}_{2}\text{(cod)}](0.020 g, 0.053 mmol) in CH₂Cl₂ (1 cm³) and stirred for 24 hours. In air, the product was then precipitated in hexane (ca. 25 cm³). After the mixture was allowed to settle, the supernatant was removed using a pipette and the residual solvent removed in vacuo to give the product as a pale yellow solid (0.043 g, 95%). \( \text{rac:meso} \) compounds observed in 1:1 ratio.

\[ \text{[PtbCl}_{2}\text{(L}_3\text{)}\text{]}(1\text{c}) \]

A solution of \( L_3 \) (0.018 g, 0.058 mmol) in CH₂Cl₂ (1 cm³) was added to a solution of \([\text{PtbCl}_{2}\text{(cod)}](0.010 g, 0.027 mmol) in CH₂Cl₂ (1 cm³) and stirred for 24 hours. In air, the product was then precipitated in hexane (ca. 25 cm³). After the mixture was allowed to settle, the supernatant was removed using a pipette and the residual solvent removed in vacuo to give the product as a pale yellow solid (0.022 g, 8%). Crystals suitable for X-ray diffraction were grown by slow diffusion of hexane into a CH₂Cl₂ solution of the product. \( \text{rac:meso} \) compounds observed in 3:2 ratio.
A solution of \( \text{La}_6 \) (0.040 g, 0.110 mmol) in \( \text{CH}_2\text{Cl}_2 \) (1 cm\(^3\)) was added to a solution of [PtCl\(_2\)(cod)] (0.020 g, 0.053 mmol) in \( \text{CH}_2\text{Cl}_2 \) (1 cm\(^3\)) and stirred for 24 hours. In air, the product was then precipitated in hexane (ca. 25 cm\(^3\)). After the mixture was allowed to settle, the supernatant was removed using a pipette and the residual solvent removed in vacuo to give the product as a pale yellow solid (0.035 g, 66%). Crystals suitable for X-ray diffraction were grown by slow diffusion of hexane into a \( \text{CH}_2\text{Cl}_2 \) solution of the product. rac : meso compounds observed in 3 : 1 ratio. \(^1\)H NMR (500 MHz, CD\(_2\)Cl\(_2\)): \( \delta \) 8.96 (d, \( J_{3H,1H} = 5.0 \) Hz) and 8.93 (d, \( J_{3H,1H} = 5.0 \) Hz) (total 2H, ArH (H-6)), 8.29 (br s) and 8.26 (br s) (total 2H, ArH (H-3)), 7.53 (d, \( J_{7H,1H} = 4.4 \) Hz) and 7.50 (d, \( J_{7H,1H} = 4.7 \) Hz) (total 2H, ArH (H-5)), 3.02 (d of vir t, \( J_{7H,1H} = 13.7 \) Hz, \( J_{H,P} = 2.3 \) Hz) and 2.93 (d of vir t, \( J_{7H,1H} = 13.7 \) Hz, \( J_{H,P} = 2.4 \) Hz) (total 2H, \( \text{CgP CH}_3 \)), 1.98–1.86 (m, 4H, \( \text{CgP CH}_3 \)), 1.84–1.71 (m, 12H, \( \text{CgP CH}_3 \)), 1.69–1.67 (m, 2H, \( \text{CgP CH}_3 \)), 1.41 (s) and 1.36 (s) (total 6H, \( \text{CgP CH}_3 \)), 1.28 (s, 6H, \( \text{CgP CH}_3 \)). \(^{13}\)C\(^{1}\)H NMR (126 MHz, CD\(_2\)Cl\(_2\)): \( \delta \) 156.9 (vir t, \( J_{C,P} = 33.7 \) Hz, ArC (C-2)), 151.0 (vir t, \( J_{C,P} = 8.2 \) Hz, ArC (C-6)), 137.3 (q of vir t, \( J_{C,P} = 33.9 \) Hz, \( J_{C,P} = 3.6 \) Hz, ArC (C-4)), 126.8–126.6 (m, ArC (C-3)), 123.2 (q, \( J_{C,P} = 273.5 \) Hz, ArC (C-1)), 118.4 (q, \( J_{C,P} = 3.5 \) Hz, ArC (C-5)), 97.0–96.9 (m, \( \text{CgP quat. C} \)), 75.7 (vir t, \( J_{C,P} = 14.0 \) Hz, \( \text{CgP quat. C} \)), 74.5 (vir t, \( J_{C,P} = 11.0 \) Hz, \( \text{CgP quat. C} \)), 42.6 (vir t, \( J_{C,P} = 4.0 \) Hz, \( \text{CgP CH}_3 \)), 42.5 (s, \( \text{CgP CH}_3 \)), 27.9 (s, \( \text{CgP CH}_3 \)), 27.7 (s) and 27.6 (s) (\( \text{CgP CH}_3 \)), 27.5 (br s) and 27.4 (br s) (\( \text{CgP CH}_3 \)), 26.0 (vir t, \( J_{C,P} = 2.5 \) Hz) and 25.9 (vir t, \( J_{C,P} = 2.5 \) Hz) (\( \text{CgP CH}_3 \)). \(^{19}\)F NMR (377 MHz, CD\(_2\)Cl\(_2\)): \( \delta \) -65.13 (s) and -65.16 (s) (Ar-CF\(_3\)). \(^{31}\)P\(^{1}\)H NMR (162 MHz, CD\(_2\)Cl\(_2\)): \( \delta \) 1.2 (s, \( J_{P,P} = 2750 \) Hz) and 0.7 (s, \( J_{P,P} = 2750 \) Hz) (\( \text{CgP} \)). HRMS (ESI): m/z calc. for \( \text{C}_{32}\text{H}_{38}\text{Cl}_2\text{F}_6\text{N}_2\text{O}_6\text{P}_2\text{Pt} \) [M – Cl] \(^{+}\) = 952.1443; obs. = 952.1479. Elem. Anal. found (calc. for \( \text{C}_{32}\text{H}_{38}\text{Cl}_2\text{F}_6\text{N}_2\text{O}_6\text{P}_2\text{Pt} \) [M – Cl] \(^{+}\))
[**PdCl₂(L₂)₃**] (4). A solution of L₂ (0.103 g, 0.350 mmol) in 
CH₃Cl₂ (2 cm³) was added to a solution of [PdCl₂(cod)] (0.050 g, 0.175 mmol) in CH₂Cl₂ (2 cm³) and stirred for 24 hours. In air, the product was then precipitated in hexane (ca. 25 cm³). After the mixture was allowed to settle, the supernatant was removed using a pipette and the residual solvent removed in vacuo to give the product as a yellow solid (0.129 g, 96%). *rac* meso compounds observed in 1:1 ratio. **₁H NMR** (500 MHz, CDCl₃): δ₁H = 7.83 (d, J₁H,H = 4.3 Hz) and 8.71 (d, J₁H,H = 4.4 Hz) total 2H, ArH (H-6)), 8.01 (d, 7.4 Hz) total 2H, ArH (H-3)), 7.70–7.76 (m, 2H, ArH (H-4)), 7.29 (appq, J₁H,H = 4.4 Hz, 2H, ArH (H-5)), 3.04 (d of vir t, J₂H,H = 13.6 Hz, J₁H,P = 2.3 Hz) and 2.96 (d of vir t, J₂H,H = 13.6 Hz, J₁H,P = 2.3 Hz) total 2H, CgP CH₂), 2.24 (s) and 2.35 (s) total 1H, CgP CH₂), 1.99–1.89 (m, 3H, CgP CH₂), 1.84 (vir t, J₂H,P = 6.3 Hz) and 1.80 (vir t, J₂H,P = 6.3 Hz) total 6H, CgP CH₂), 1.73 (vir t, J₁H,P = 6.8 Hz) and 1.70 (vir t, J₁H,P = 6.6 Hz) total 6H, CgP CH₂), 1.59–1.54 (m, 2H, CgP CH₂), 1.38 (s) and 1.35 (s) total 6H, CgP CH₂), 1.27 (s, 6H, CgP CH₂). **³¹P** NMR (126 MHz, CDCl₃): δ₁P = 155.6 (vir t, J₁P,P = 30.4 Hz) and 156.0 (vir t, J₁P,P = 29.7 Hz) ArC (C-2)), 150.1 (appq), J₁P,P = 8.0 Hz, ArC (C-6)), 135.4 (br s, ArC (C-4)), 131.1 (vir t, J₁P,P = 8.7 Hz) and 130.1 (vir t, J₁P,P = 8.2 Hz) ArC (C-3), 124.5 (s, ArC (C-5)), 97.0–96.8 (m, CgP quat. C), 76.3 (vir t, J₁P,P = 10.9 Hz) and 76.2 (vir t, J₁P,P = 10.8 Hz) (CgP quat. C), 75.0 (vir t, J₁P,P = 7.1 Hz) and 74.8 (vir t, J₁P,P = 7.0 Hz) (CgP quat. C), 43.2–43.1 (m, CgP CH₂), 42.5–42.4 (m, CgP CH₂), 28.2 (br s) and 28.1 (br s) (CgP CH₂), 27.8 and 27.3 (s) (CgP CH₂), 24.6 (br s) and 26.3 (br s) (CgP CH₂), 1.56 (s) and 1.55 (s) (Si(CH₃)₃). **³¹P** NMR (202 MHz, CD₂Cl₂): δ₁P = 1.6 (s, J₁P,P = 2722 Hz) and -1.9 (s, J₁P,P = 2724 Hz) (CgP)(HRMS (ESI): *m/z* calc. for C₅₀H₅₀Cl₄N₄P₂O₄Pt[Pd [M + Cl]⁻] = 996.2251; obs = 996.2247. Elemental analysis (calc. for C₅₀H₅₀Cl₄N₄O₂P₄Pt[Pd [M + Cl]⁻] = 727.1088; obs = 727.1103. *rac* CgP=Cg(1-C₂)(5-C₂)BF₄ [5BF₄]). AgBF₄ (0.008 g, 0.039 mmol) was added to a CH₁Cl₂ solution (3 cm³) of 4 (0.030 g, 0.039 mmol) and stirred overnight. The cloudy mixture was then filtered through Celite to give a yellow solution, which was then added to hexane to precipitate the product. After the mixture was allowed to settle, the supernatant was removed using a pipette and the residual solvent removed in vacuo to give the product as a yellow solid (0.042 g, 76%). Crystals suitable for X-ray diffraction were grown by slow evaporation of a
CH$_2$Cl$_2$ solution of the product. $^1$H NMR (500 MHz, CD$_2$Cl$_2$): $\delta$ 8.92–8.89 (m, 1H, ArH), 8.79–8.78 (m, 1H, ArH), 8.41–8.36 (m, 1H, ArH), 8.06–8.02 (m, 2H, ArH), 7.87–7.79 (m, 2H, ArH), 7.79–7.47 (m, 1H, ArH), 2.43–1.27 (m, 32H, CgP CH$_2$ and CgP CH$_3$). $^{11}$B($^1$H) NMR (128 MHz, CD$_2$Cl$_2$): $\delta$ _B_ = 2.2 (s, BF$_4$). $^{31}$P NMR (377 MHz, CD$_2$Cl$_2$): $\delta$ _P_ = 152.8 (s, BF$_4$). $^{31}$P($^1$H) NMR (121 MHz, CD$_2$Cl$_2$): $\delta$ _P_ = 28.8 (br s, monodentate CgP), −42.1 (d, $^3$J$_{P,P}$ = 3.2 Hz, chelate CgP). $^{31}$P($^1$H) NMR (121 MHz, CD$_2$Cl$_2$−90 °C): $\delta$ _P_ = 28.8 (d, $^3$J$_{P,P}$ = 3.2 Hz, monodentate CgP), −42.0 (br s, chelate CgP). HRMS (ESI): m/z calc. for C$_{10}$H$_{16}$ClO$_2$P$_2$Pd·CH$_2$Cl$_2$: [M] + = 727.1088; obs. = 727.1118. Elem. Anal. found (calc. for C$_{10}$H$_{16}$ClO$_2$P$_2$Pd·CH$_2$Cl$_2$): C, 41.79 (41.76); H, 4.86 (4.70); N, 3.20 (3.11) (the presence of CH$_2$Cl$_2$ was confirmed by $^1$H NMR spectroscopy and was observed in the crystal structure).

Protonation studies

TsOH·H$_2$O (0.003 g, 0.015 mmol) was added to a suspension of 4 (0.010 g, 0.013 mmol) in CD$_2$Cl$_2$ (0.7 cm$^3$), upon which the solution became homogeneous, yielding species assigned to the protonated species 6. $^{31}$P($^1$H) NMR (121 MHz, CD$_2$Cl$_2$): $\delta$ _P_ = 6.0 (br s, CgP) and 3.7 (br s, CgP). An analogous procedure in MeOH (0.7 cm$^3$) also gave a homogenous solution, assigned to be a mixture of 6 and a P,N-chelate species related to [5OTs].

Phenylacetylene methoxycarbonylation

Adapted from previously reported procedure. Catalysis was performed using a Baskerville Multi-Cell autoclave. The ligand (0.11 mmol) was added to the autoclave and the system put under an atmosphere of N$_2$. Solutions of Pd(OAc)$_2$ (0.0055 mmol) in MeOH (0.5 cm$^3$) and TsOH·H$_2$O (0.22 mmol) in MeOH (0.5 cm$^3$) were then added, followed by phenylacetylene (5.5 mmol). This was then washed in using MeOH (0.5 cm$^3$) and the autoclave flushed with three cycles of CO (ca. 10 bar). The autoclave was then pressurised to 45 bar and heated to 60 °C. After 1 hour or 4.5 hours, the autoclave was transferred to an ice bath and once cooled, the system was vented. A small amount of each sample was dissolved in CDCl$_3$ and analysed by $^1$H NMR spectroscopy. Conversion and selectivity was determined by integration of the phenylacetylene alkynyl proton ($\delta$$_H$ 3.10 ppm) and the methyl atropate ($\delta$$_H$ 6.38 and 5.90 ppm) and methyl cinnamate ($\delta$$_H$ 7.71 and 6.42 ppm) alkynyl protons.

X-ray crystallography

All of the X-ray diffraction data were collected at 100 K on a Bruker Apex II diffractometer with CCD area detector using Mo-Kα radiation ($\lambda$ = 0.71073 Å). Absorption corrections were carried out using SADABS.$^{25}$ All of the structures were solved using Superflip$^{26,27}$ and refined by full matrix least squares on $F^2$ using ShelXL$^{28,29}$ within Olex2.$^{30}$ The structure of meso-1g displayed disorder in the cage, the occupancies of the disordered atoms were refined with the sum of the occupancies set to 1 before being fixed at the refined values. Restraints were applied to the bond lengths and the thermal parameters of pairs of disordered atoms on almost the same site were constrained to be equal. The structure of 5 was twinned and refined as a 2-component twin. In addition, the BF$_4$ counterion displayed disorder in the fluorene positions, the sum of the occupancies were set to equal 1 and refined before being fixed at the refined values. Restraints were applied to maintain sensible thermal parameters and B-F distances. Crystal structure and refinement details are given in Tables S1–S3 in ESI.$^1$ Crystallographic data for the compounds have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication, CCDC 1497885–1497898.

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References


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