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Transition metal (Rh and Fe) complexes and main-group (Se and B) adducts with *N,N′*-diphosphanyl NHC ligands: a study of stereoelectronic properties†

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Attempts to evaluate experimentally the donor characteristics of the *N,N′*-bis(di-*tert*-butylphosphanyl)-imidazole-2-ylidene (**PC$_{NHC}$P**) hybrid ligand are described. Thus, reactions of **PC$_{NHC}$P** with [Rh(μ-Cl)(COD)]$_2$ and [Rh(μ-Cl)(CO)$_2$]$_2$ led to the formation of the mononuclear and dinuclear complexes, [Rh(**PC$_{NHC}$P**,κ*P*,κ*C*$_{NHC}$)$_2$]Cl (**PC$_{NHC}$P-RhCl**) and [Rh(CO)(**PC$_{NHC}$**,κ*P*,κ**C$_{NHC}$**,κ*N*)]$_2$ (**PC$_{NHC}$-RhCO**), respectively, the latter resulting after *in situ* cleavage of one (*t*-Bu)$_2$P–N$_{imid}$ bond of **PC$_{NHC}$P**. With ligands acting as a P,C-chelate, a straightforward evaluation of the Tolman electronic parameter (TEP) of the C$_{NHC}$ donor is problematical; the viability of dangling P- and bound C$_{NHC}$-donors (*i.e.* κC$_{NHC}$) has been observed in the trinuclear Fe(II) chain complex [Fe$_3$Cl$_2$(μ-Cl)$_4$(THF)$_2$(**PC$_{NHC}$P**,κ**C$_{NHC}$**)$_2$] (**PC$_{NHC}$P-Fe**), obtained by the reaction of **PC$_{NHC}$P** with [Fe$_4$Cl$_8$(THF)$_6$] and, recently, established on Cr^{II}, Co^{II} and Au^{I} centres. Evaluation of the π-accepting properties of the **PC$_{NHC}$P** (and the related **Dipp-PC$_{NHC}$**) was based on the ^{77}Se NMR chemical shifts of the corresponding NHC–Se adducts, **PC$_{NHC}$P-Se** (and **Dipp-PC$_{NHC}$-Se**), which were prepared from the free **PC$_{NHC}$P** (and **Dipp-PC$_{NHC}$**) and Se. The π-acidity of **PC$_{NHC}$P** is found to be higher than that of **Dipp-PC$_{NHC}$** but lower than that of **SIPr**. The donor ability of the C$_{NHC}$ in **PC$_{NHC}$P** was explored by its reaction with the Lewis acids tris(pentafluorophenyl)borane (B(C$_6$F$_5$)$_3$) and tris(pentafluorophenyl)boroxine ([(C$_6$F$_5$)BO]$_3$), which resulted in stable donor–acceptor adducts with no FLP reactivity. The steric properties of **PC$_{NHC}$P** and **Dipp-PC$_{NHC}$** are conformation dependent, with the percent buried volume (%V$_{bur}$) of **PC$_{NHC}$P** in the structurally characterised conformer calculated at 67.6, the largest value currently reported for NHC ligands.

Introduction

N-heterocyclic carbene (NHC) ligands have become ubiquitous in molecular chemistry and find extensive applications in *e.g.* catalytic transformations, medicinal chemistry and material sciences.[1] Both experimental and theoretical studies on their electronic properties have established synergism resulting from their strong σ donor and weaker π acceptor properties. The most commonly used method for the experimental evaluation of the donor properties of NHCs is the Tolman electronic parameter (TEP), originally developed for phosphines by Tolman in 1970,[2] which is based on the value of the A_1 ν(CO) infrared-stretching frequencies in [Ni(CO)$_3$L], or the average ν(CO) frequencies in *cis*-[Ir(CO)$_2$ClL] and *cis*-[Rh(CO)$_2$ClL] (Chart 1), the latter two complexes being more widely used nowadays owing to the toxicity of [Ni(CO)$_4$].[2,3] However, the TEP quantifies the overall NHC electronic properties and does not separate the σ donation and π back-donation components.

Recently, Bertrand and coll.[4] and Ganter and coll.[5] separately reported the use of phosphinidene (NHC)PPh and selenium adducts (NHC)Se (Chart 1) to probe the NHC π back-bonding ability, on the basis of the δ$_p$ chemical shift in the ^{31}P NMR and the δ$_{Se}$ chemical shift in the ^{77}Se NMR, respectively. These adducts can be represented by two limiting canonical structures: the polarized form **A** with a NHC–E (E = PPh or Se) single bond indicating little π accepting ability and the resonance form **B** with a NHC–E (E = PPh or Se) double bond consistent with a high π accepting ability of NHCs. In contrast to the narrow range of TEP values, the chemical shifts of the phosphinidene/selenium adducts are very sensitive to subtle changes of the electronic structures of NHCs and offer a finer grading of the NHCs.

Various groups have recently reported *N*-phosphanyl-functionalized NHC ligands, which feature the two adjacent, strong σ-donors groups linked by a direct P–N bond.[6] Because of the

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† Electronic supplementary information (ESI) available: Crystal data for **PCP-RhCl**·2CH$_2$Cl$_2$, **PC$_{NHC}$-RhCO**, **PC$_{NHC}$P-Fe**, **PC$_{NHC}$P-Se**, **PC$_{NHC}$P-B1**·THF and **PC$_{NHC}$P-B2**·toluene. CCDC 1449234–1449239. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/c6dt00318d

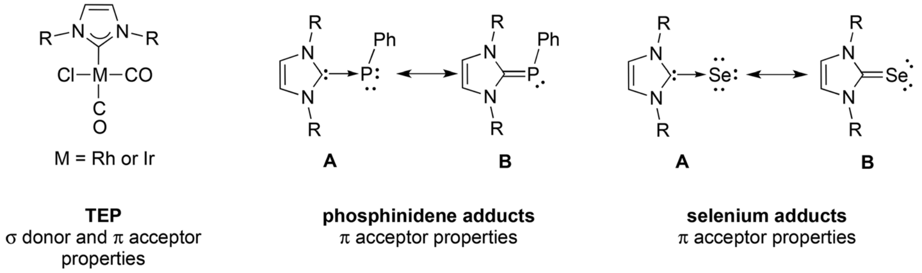


Chart 1 Three experimental methods used to evaluate the electronic properties of NHC ligands.

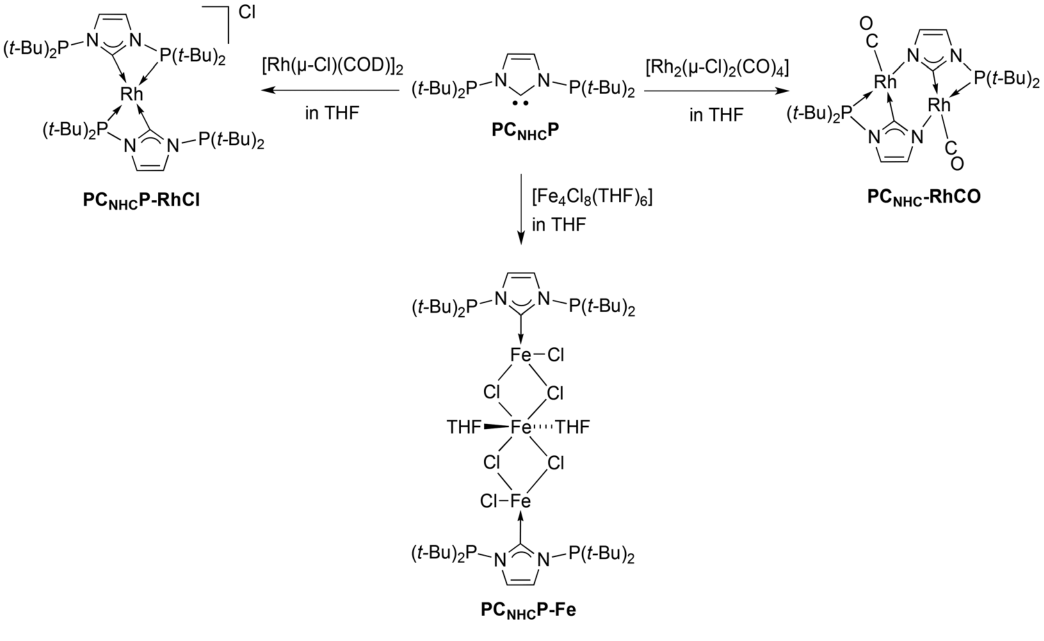
rigidity and ease of tuning of their steric and electronic properties, they have not only been used as bridging ligands for d^{10} coinage metals but also as small bite angle (*ca.* 68.2°) chelating ligands for platinum group or late transition metals.[6c–f,7] We have recently reported the synthesis of the new tridentate ligand *N*,*N*′-bis(di-*tert*-butylphosphanyl)-imidazole-2-ylidene (**PC$_{\text{NHC}}$P**) (Scheme 1) and its behaviour as bridging ligand with coinage metals or palladium, resulting in polynuclear complexes,[6h,i,8] and as **PC$_{\text{NHC}}$** chelating ligand with chromium or palladium.[8a,9] However, a more precise experimental estimate of the stereoelectronic properties of C_{NHC} donor in the **PC$_{\text{NHC}}$P** ligand is not straightforward, due to the high nucleophilicity of both donors and the propensity of formation of small ring chelates with the metals used as probes for the TEP. Herein, we describe Rh(I) carbonyl complexes with **PC$_{\text{NHC}}$P** which display κ*P*, κC_{NHC} coordination, thus rendering the evaluation of the TEP cumbersome; in contrast, the selective access of NHC–Se adducts permits the evaluation of the π accepting ability of the C_{NHC} in **PC$_{\text{NHC}}$P**; furthermore we give an estimate of the steric bulk of **PC$_{\text{NHC}}$P**, and describe adducts with $B(C_6F_5)_3$ and $FeCl_2$ in which C_{NHC} coordination predominates.

Results and discussion

Mono- and dinuclear rhodium complexes and trinuclear iron complex

Since no rhodium complex with the **PC$_{\text{NHC}}$P** has yet been prepared, with the objective to prepare *cis*-[RhCl(CO)$_2$(**PC$_{\text{NHC}}$P**)] we firstly reacted **PC$_{\text{NHC}}$P** with [Rh(μ-Cl)(COD)]$_2$ in THF in a 1 : 1 ligand/Rh ratio (Scheme 1). However, instead of the expected adduct [RhCl(COD)(**PC$_{\text{NHC}}$P**,κ*C*$_{\text{NHC}}$)], the mononuclear complex [Rh(**PC$_{\text{NHC}}$P**,κ*P*,κ*C*$_{\text{NHC}}$)$_2$]Cl (**PC$_{\text{NHC}}$P-RhCl**) was isolated, the two **PC$_{\text{NHC}}$P** ligands acting as P,C-chelates. This was confirmed by single-crystal X-ray diffraction analysis (Fig. 1).

The unit cell of **PC$_{\text{NHC}}$P-RhCl** contains two similar complex cations with slightly different metrical data and isolated chloride anions (Rh–Cl distance 7.418/7.359 Å). In each cation, the tetracoordinated Rh atom occupies a centre of symmetry and is chelated by two **PC$_{\text{NHC}}$P** ligands through their C_{NHC} and one phosphorus donor, with a bite angle of 67.26(11)/67.31(13)°. The solution $^{31}P\{^1H\}$ NMR spectrum of **PC$_{\text{NHC}}$P-RhCl** contains a doublet at δ 113.1 (^1J(P–Rh) = 146.9 Hz) and a singlet at δ 83.8,



Scheme 1 Reactions of PC$_{\text{NHC}}$P with [Rh(μ-Cl)(COD)]$_2$, [Rh(μ-Cl)(CO)$_2$]$_2$ and [Fe$_4$Cl$_8$(THF)$_6$].

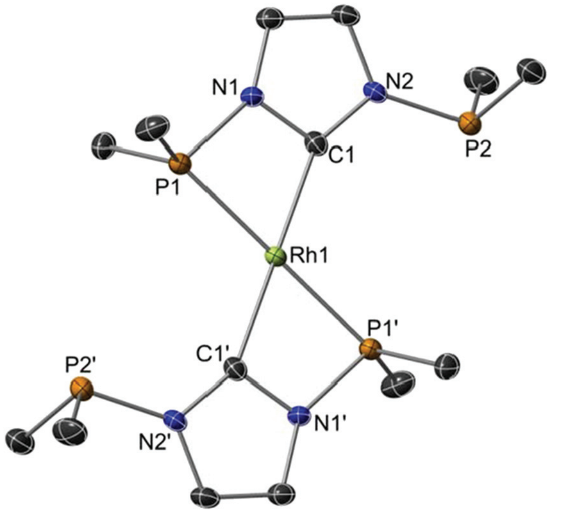


Fig. 1 Thermal ellipsoid representation (30% probability level) of the structure of one cation in **PC$_{NHC}$P-RhCl**. H atoms, the *t*-Bu methyl groups, the second complex cation and the chloride anions are omitted for clarity. Selected bond lengths (Å) and angles [°] (the two values are for the two independent cations in the unit cell): Rh1–C1 2.077(4)/2.082(4); Rh1–P1 2.300(1)/2.304(1), C1–Rh1–P1 67.26(11)/67.31(13).

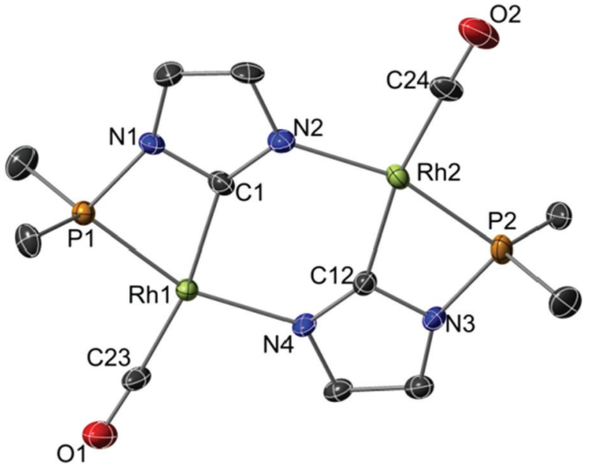


Fig. 2 Thermal ellipsoid representation (30% probability level) of the structure of **PC$_{NHC}$-RhCO**. H atoms and the *t*-Bu methyl groups are omitted for clarity. Selected bond lengths (Å) and angles [°]: Rh1–C1 2.071(10), Rh2–C12 2.080(9), Rh1–C23 1.833(10), Rh2–C24 1.842(11), Rh1–N4 2.080(8), Rh2–N2 2.065(8), Rh1–P1 2.249(3), Rh2–P2 2.243(3), C23–O1 1.166(12), C24–O2 1.152(12); C1–Rh1–P1 67.3(3), C12–Rh2–P2 67.2(3).

corresponding to the coordinated and the uncoordinated phosphines, respectively. The latter value is slightly different from that of the free **PC$_{NHC}$P** (δ 98.7),[6h] indicating electronic communication between the P donors on coordination.

In view of the lability of the COD ligand that prevented the preparation of [RhCl(COD)(**PC$_{NHC}$P**)], the complex [Rh(μ-Cl)(CO)$_2$]$_2$ was used as precursor and was directly reacted with **PC$_{NHC}$P** in THF. However, instead of the expected *cis*-[RhCl(CO)$_2$(**PC$_{NHC}$P**,κ*C*$_{NHC}$)], the neutral, dinuclear complex [Rh(CO)(**PC$_{NHC}$**,κ*P*,κ*C*$_{NHC}$,κ*N*)]$_2$ (**PC$_{NHC}$-RhCO**) containing two monoanionic **PC$_{NHC}$** ligands was obtained after cleavage of one (*t*-Bu)$_2$P–N$_{imid}$ bond of **PC$_{NHC}$P** (Scheme 1). The formation of (*t*-Bu)$_2$PCl was evidenced in the reaction mixture as the only other P-containing product (δ 145 in ^{31}P{^{1}H} NMR). A similar P–N bond cleavage reaction has also been observed when **PC$_{NHC}$P** was reacted with [AuCl(tht)] and rationalised by the reactivity of the P–N bond toward the nucleophilic chloride ligand.[6i] The ^{31}P{^{1}H} NMR spectrum of **PC$_{NHC}$-RhCO** contains a doublet at δ 128.4 (^1J(P–Rh) = 142.8 Hz). The structure of this complex exhibits an approximate C_2 symmetry and the square-planar environment around each Rh atom contains one chelating **PC$_{NHC}$** ligand, bonded through the P and C$_{NHC}$ 2 electron donors which form an angle of 67.3(3)/67.2(3)°, a negatively charged N atom from the other **PC$_{NHC}$** ligand and one carbonyl ligand *trans* to C$_{NHC}$ (Fig. 2). Related dinuclear rhodium complexes with bridging arylimidazolide-*N*^{3},*C*^{2} ligands containing a central six-membered ring have been recently reported.[10]

Since **PC$_{NHC}$** chelation was observed here with **PC$_{NHC}$P-RhCl** and previously with Pd(II) and Cr(III) centres,[8a,9] but not with Cr(II) or Co(II),[9,11] we wondered whether the κ*C*$_{NHC}$ coordination mode is more common with 3d metals. Thus, reaction of **PC$_{NHC}$P** with [Fe$_4$Cl$_8$(THF)$_6$] in THF inside a glovebox (Scheme 1) afforded colourless, paramagnetic, air-sensitive crystals after crystallisation by addition of pentane. Single-crystal X-ray diffraction established the formation of a centrosymmetric trinuclear Fe(II) chain complex [Fe$_3$Cl$_2$(μ-Cl)$_4$(THF)$_2$(**PC$_{NHC}$P**,κ*C*$_{NHC}$)$_2$] (**PC$_{NHC}$P-Fe**) in which each outer Fe atom is coordinated to the C$_{NHC}$ donor of one **PC$_{NHC}$P** ligand, with both P donors remaining uncoordinated (Fig. 3). The linear metal chain is assembled by two μ-chlorido ligands that connect the outer Fe atoms to the central Fe2. The outer Fe atoms adopt a tetrahedral coordination geometry consisting of three chloride ligands and one C$_{NHC}$ donor while the central iron is in an octahedral environment with four chloride ligands occupying equatorial positions and two THF molecules the axial positions. The higher occurrence of this coordination mode with 3d metals may be rationalised by the reduced M–P bond energies and the reduced size and strength of ligand fields of 3d rendering structures with dangling P donors energetically more accessible compared to 4d and 5d metals.

NHC adducts with main group elements (Se, B)

Based on the results we shifted our attention to alternative adducts that may disclose information on the donor characteristics of the **PC$_{NHC}$P**. The first attempt focused on the synthesis of phosphinidene adducts of NHCs, which carry information on the π-accepting strength of the NHC precursor.[4] Two known synthetic routes were explored for the synthesis of the adducts (Scheme 2): (i) the direct reaction of **PC$_{NHC}$P** with pentaphenylcyclopentaphosphane ((PPh)$_5$); (ii) the reaction of **PC$_{NHC}$P** with PhPCl$_2$ followed by reduction with Mg. However, both failed: the former gave no reaction even after heating to 70 °C, and the latter led to the cleavage of a P–N bond of **PC$_{NHC}$P** by PhPCl$_2$ with formation of (*t*-Bu)$_2$PCl.

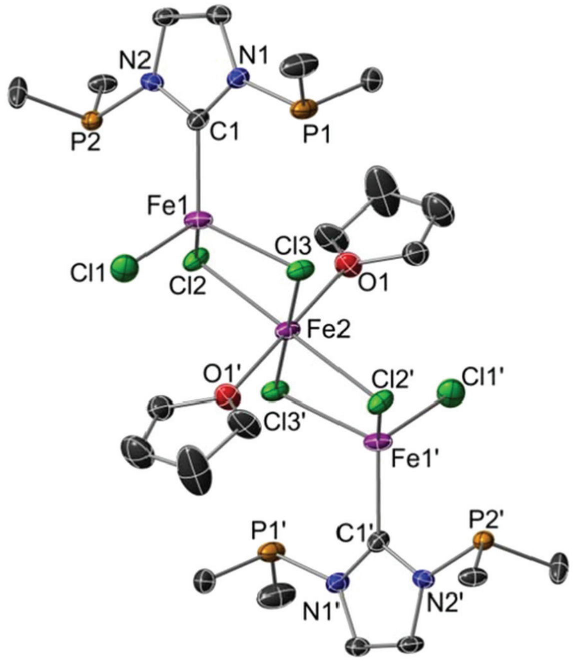


Fig. 3 Thermal ellipsoid representation (30% probability level) of the structure of **PC_{NHC}P-Fe**. H atoms and the *t*-Bu methyl groups are omitted for clarity. Selected bond lengths (Å) and angles [°]: Fe1–C1 2.103(6), Fe1–Cl1 2.2587(19), Fe1–Cl2 2.3807(17), Fe1–Cl3 2.4118(18), Fe2–Cl2 2.4781(14), Fe2–Cl3 2.4755(14), Fe2–O1 2.158(4); Fe1–Cl2–Fe2 91.98(5), Fe1–Cl3–Fe2 91.30(5), C1–Fe1–Cl1 112.98(16), C1–Fe1–Cl2 115.81(15), C1–Fe1–Cl3 115.31(16), Cl1–Fe1–Cl2 111.90(7), Cl1–Fe1–Cl3 109.59(6), Cl2–Fe1–Cl3 88.99(6), O1–Fe2–Cl3′ 88.33(11).

The second attempt focused on the synthesis of selenium adducts; herein, the π-accepting properties of NHCs precursors can also be correlated with the ^{77}Se NMR chemical shift observed.[5] Thus, reaction of elemental selenium with **PC_{NHC}P** in a 1 : 1 ratio in THF afforded selectively the desired adduct **PC_{NHC}P-Se**, with intact phosphine groups (Scheme 2), as indicated by a ^{31}P NMR shift (s, δ 91.0) (*cf.* **PC_{NHC}P** δ s, 98.7). The structure of the product was further confirmed by an X-ray diffraction analysis (Fig. 4). The Se–C_{NHC} bond distance 1.839(8) Å is intermediate between that of a Se–C single bond (aver. 1.94 Å) and of a typical Se═C double bond (aver. 1.74 Å).[12] Its value is similar to that found in other selenium–NHC adducts.[5b,12a–c] Compared to the free carbene **PC_{NHC}P**, the N–C_{NHC} bond lengths (1.36(1)/1.370(9) Å, *cf.* 1.376(1)/1.378(1) Å in **PC_{NHC}P**) are shortened and the N1–C1–N2 angle (108.2(6)°, *cf.* 102.5(1)° in **PC_{NHC}P**) enlarged.

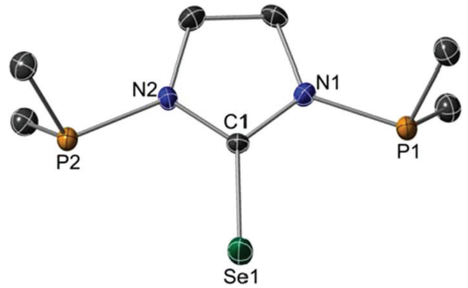
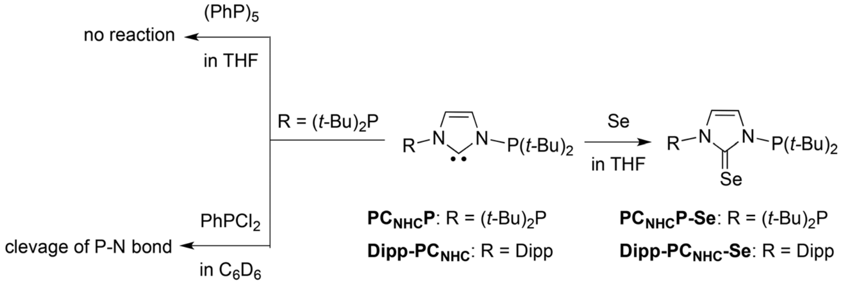


Fig. 4 Thermal ellipsoid representation (30% probability level) of the structure of **PC_{NHC}P-Se**. H atoms and the *t*-Bu methyl groups are omitted for clarity. Selected bond lengths (Å) and angles [°]: C1–Se1 1.839(8), C1–N1 1.36(1), C1–N2 1.370(9), N1–P1 1.760(7), N2–P2 1.775(7); N1–C1–N2 108.2(6).

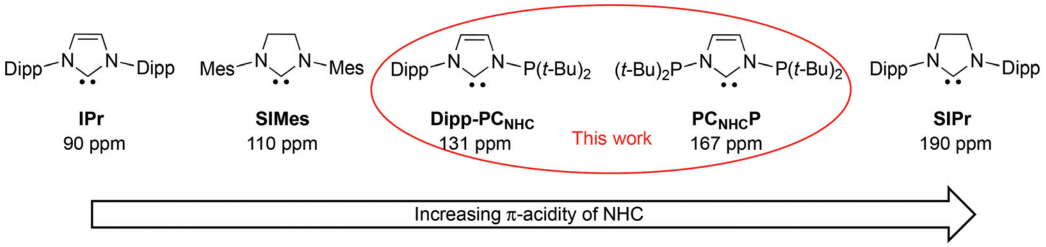
For comparison with **PC_{NHC}P-Se**, the selenium adduct **Dipp-PC_{NHC}-Se** of a ligand containing only one phosphine group was prepared under similar reaction conditions (Scheme 2). The ^{77}Se NMR spectra feature a triplet at δ 166.9 ($^{2}J_{SeP}$ = 46.5 Hz) for **PC_{NHC}P-Se** and a doublet at δ 131.1 ($^{2}J_{SeP}$ = 40.0 Hz) for **Dipp-PC_{NHC}-Se.** Accordingly, and by comparison with literature data, it can be concluded that the π-acidity of **PC_{NHC}P** is stronger than that of **Dipp-PC_{NHC}** and that both ligands are stronger π-acids than **SIMes** (δ 110 ^{77}Se NMR), but weaker π-acids than **SIPr** (δ 190 ^{77}Se NMR) (Scheme 3).[13]

To further explore the donor abilities of the C_{NHC} and P donors in **PC_{NHC}P,** the latter was reacted with tris(pentafluorophenyl)borane $B(C_6F_5)_3$ in toluene (Scheme 4). The ^{11}B NMR spectrum of the resulting product (**PC_{NHC}P-B1**) shows a single resonance at δ −17.5, which is indicative of a four-coordinate boron centre and suggests the formation of a NHC–borane Lewis adduct with a stable B–C_{NHC} bond.

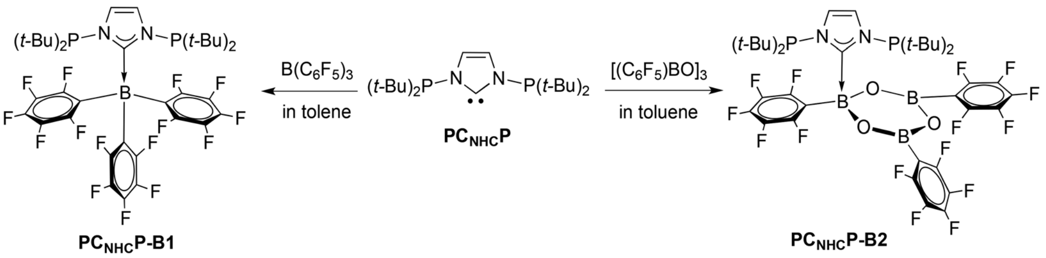
Broad NMR resonances were not only observed for the three pentafluorophenyl groups in the ^{19}F NMR and ^{13}C NMR spectra but also for the phosphine groups (one broad singlet at δ 110.5) and C_{NHC} (broad multiplet at δ 177.1). This, together with the singlet at δ 7.69 for the two protons on the imidazolylidene ring, indicates fast free rotation of the $B(C_6F_5)_3$ moiety around the B–C_{NHC} bond. A single-crystal



Scheme 2 Reactions of **PC_{NHC}P** and **DIPP-PC_{NHC}** with $PhPCl_2$, $(PPh)_5$ and elemental selenium.



Scheme 3 Comparative π-acidity of NHC ligands based on the ^{77}Se NMR data (in $CDCl_3$).



Scheme 4 Synthesis of the adducts **PC$_{NHC}$P-B-1** and **PC$_{NHC}$P-B-2**.

X-ray diffraction analysis showed that the three C_6F_5 groups adopt a typical C_3 propeller-type orientation (Fig. 5). For steric reasons, the lone pair on the P atoms is oriented toward the borane moiety.

Unlike other NHC–borane adducts,[14] **PC$_{NHC}$P-B1** exhibits no frustrated-Lewis-pair (FLP) reactivity toward H_2 or THF, which is consistent with a rather strong donor–acceptor C_{NHC} → B interaction, despite a moderate elongation of this bond (1.688(3) Å) when compared to that in the adduct **IPr**/$B(C_6F_5)_3$ (1.663(5) Å)[14a] and in 1,3,4,5-tetramethyl-1,3-imidazole-2-ylidene/$B(C_6F_5)_3$ (1.640(2) Å).[15]

Another donor–acceptor adduct was obtained by reaction of **PC$_{NHC}$P** with a suspension of tris(pentafluorophenyl)boroxine $[(C_6F_5)BO]_3$ in toluene (Scheme 4). An immediate reaction occurred with formation of a clear solution. A crystallographic analysis established again the formation of one C_{NHC} → B bond in the boroxine adduct **PC$_{NHC}$P-B2**, leaving the other two B atoms intact (Fig. 6). The B–C_{NHC} bond distance 1.670(4) Å

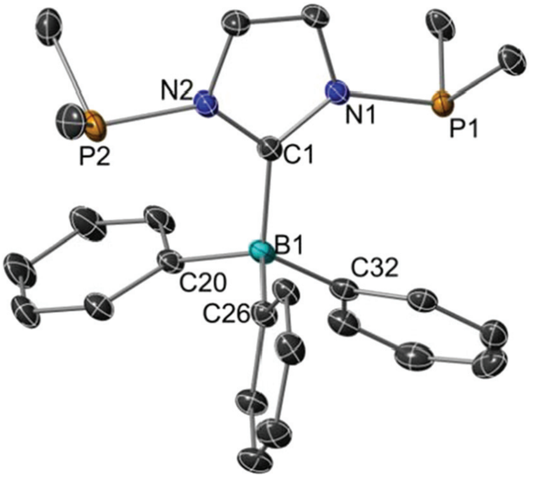


Fig. 5 Thermal ellipsoid representation (30% probability level) of the structure of **PCP-B1**. H atoms, the *t*-Bu methyl groups, all the F atoms and one molecule of THF are omitted for clarity. Selected bond lengths (Å) and angles [°]: B1–C1 1.688(3), B1–C20 1.659(3), B1–C26 1.660(3), B1–C32 1.670(3); N1–C1–N2 104.98(15), C20–B1–C26 111.11(16), C20–B1–C32 112.03(16), C26–B1–C32 101.70(15), C20–B1–C1 106.09(15), C26–B1–C1 110.95(16), C32–B1–C1 115.06(15).

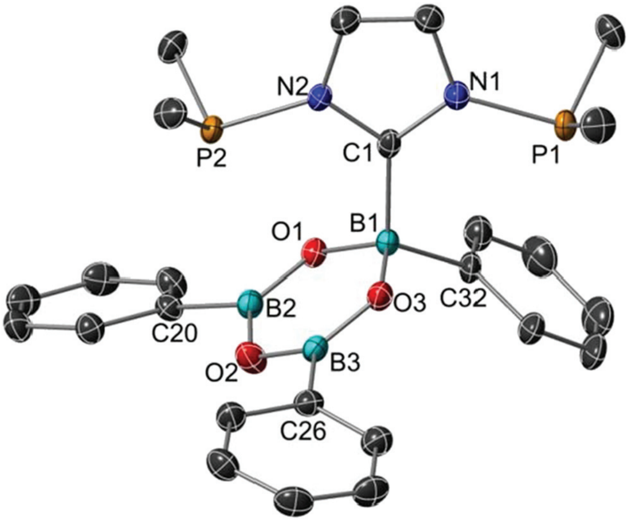
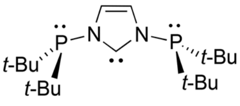
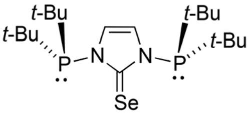
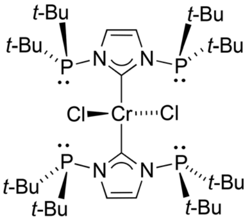
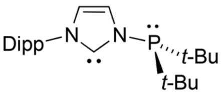
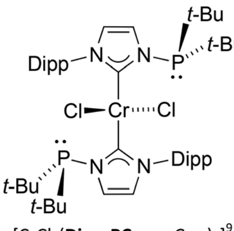


Fig. 6 Thermal ellipsoid representation (30% probability level) of the structure of **PC$_{NHC}$P-B-2**. H atoms, the *t*-Bu methyl groups, all the F atoms and one molecule of toluene are omitted for clarity. Selected bond lengths (Å) and angles [°]: C1–B1 1.670(4), C20–B2 1.590(4), C26–B3 1.586(4), C32–B1 1.643(4), N1–C1–N2 105.6(2), O1–B1–C1 108.6(2), O3–B1–C1 105.0(2), C32–B1–C1 113.7(2).

is slightly shorter than that in **PC$_{NHC}$P-B1**. Obvious differences were observed between the three B–C_6F_5 moieties: (i) the B1–C32 bond (1.643(4) Å) is elongated compared to the other two (1.590(4) Å and 1.586(4) Å); (ii) the B2–C20 and B3–C26 bonds are coplanar with the boroxine ring while the B1–C32 bond bends out of the boroxine plane, away from the **PC$_{NHC}$P** ligand with a distance of 1.393 Å between the C23 atom and the boroxine plane. This results from the coordination of B1 to C$_{NHC}$ forming a tetrahedral environment around the B1 atom.

The ^{31}P NMR spectrum shows one singlet at δ 97.6 for the phosphine groups and a doublet is observed in the ^{1}H NMR spectrum at δ 1.15 ($^3J_{HP}$ = 12.9 Hz) for the *t*-Bu groups, which indicates free rotation of the boroxine moiety around the B–C$_{NHC}$ bond. The ^{11}B NMR spectrum contains a broad signal at δ 26.4 and a singlet at δ −0.6 ppm corresponding to the three- and four-coordinate B atoms, respectively. Similarly to **PC$_{NHC}$P-B1**, it exhibited no frustrated-Lewis-pair (FLP) reactivity toward H_2 or THF.

Table 1 Percent buried volume (%V_{bur})

Compounds	%V_{bur} for M–NHC length at 2.00 Å	%V_{bur} for M–NHC length at 2.28 Å
 **PC$_{NHC}$P**	67.6	63.1
 **PC$_{NHC}$P-Se**	32.5	28.3
 [CrCl$_2$(**PC$_{NHC}$P**-κC_{NHC})$_2$][9]	36.4	31.7
 **Dipp-PC$_{NHC}$**	39.4	36.2
 [CrCl$_2$(**Dipp-PC$_{NHC}$**-κC_{NHC})$_2$][9]	35.8	31.0

Percent buried volume of the NHC ligands

Lastly, the steric properties of **PC$_{NHC}$P** and **Dipp-PC$_{NHC}$** were evaluated from the percent buried volume (%V_{bur}) using the Samb*V*ca software,[16] and metrical data from the crystal structures. The results are compiled in Table 1 assuming a 3.50 Å for the sphere radius, omitted hydrogen atoms and scaled bond radii by 1.17, as recommended. Rotation of the phosphine group around the P–N bond has dramatic effect on the steric environment at the carbene centre, especially for **PC$_{NHC}$P**. The %V_{bur} of the free carbene **PC$_{NHC}$P** reaches a value up to 67.6 (M–NHC 2.00 Å), for the conformation observed crystallographically, featuring *anti* lone pair arrangement; this value is the largest value among all reported NHC ligands (Table 1).[17] In the conformation with *syn* arrangement of the lone pairs which is commonly found on κC_{NHC} coordination or adduct formation the %V_{bur} decreases to 32.5 for **PC$_{NHC}$P-Se** and 36.4 for [CrCl$_2$(**PC$_{NHC}$P**-κC_{NHC})$_2$][9] (M–NHC 2.00 Å). Compared to the %V_{bur} values found in **PC$_{NHC}$P**, that for **Dipp-PC$_{NHC}$** is smaller (39.4, M–NHC 2.00 Å) but similar (35.8, M–NHC 2.00 Å) to that in the Cr(II) complexes.

Conclusions

Some stereoelectronic properties of the hybrid ligands **PC$_{NHC}$P** and **Dipp-PC$_{NHC}$** have been evaluated. Initial attempts to prepare *cis*-[RhCl(CO)$_2$(**PC$_{NHC}$P**-κC_{NHC})] by the reaction of **PC$_{NHC}$P** with [Rh(μ-Cl)(COD)]$_2$ or [Rh(μ-Cl)(CO)$_2$]$_2$ led instead to the formation of rhodium complexes with a chelating **PC$_{NHC}$P**,κ*P*,κC_{NHC} or **PC$_{NHC}$**,κ*P*,κC_{NHC},κ*N* ligand, and the additional coordination of the phosphine group hampered the evaluation of the TEP of the sole C$_{NHC}$ donor. However, the π-accepting properties of **PC$_{NHC}$P** and **Dipp-PC$_{NHC}$** were determined from the ^{77}Se NMR chemical shift of the corresponding selenium adducts. The σ-donor ability of the carbene donor in **PC$_{NHC}$P** was confirmed by the isolation of two stable donor–acceptor adducts with borane or boroxine. The free carbene donor of **PC$_{NHC}$P** shows the largest value reported for percent buried volume in NHC ligands in the conformation of the free **PC$_{NHC}$P** established crystallographically. Currently, it appears that a coordination mode through the C$_{NHC}$ donor (κC_{NHC}) is more common with 3d metals.

Experimental section

Synthesis and characterisation

General methods. All manipulations involving organometallics were performed under argon using standard Schlenk techniques. Solvents were dried using standard methods and distilled under nitrogen prior to use or passed through columns of activated alumina and subsequently purged with nitrogen or argon. ^{1}H, ^{13}C{^{1}H}, and ^{31}P{^{1}H} NMR spectra were recorded at 298 K, unless otherwise specified, on a Bruker Avance 400, 500 or 600 spectrometer and referenced to the residual solvent resonance (^{1}H and ^{13}C) or external 85% H_3PO_4

in D_2O (^{31}P). The ^{77}Se NMR spectra were referenced to external KSeCN in D_2O at a specific concentration with a chemical shift of −329.0 ppm (0.25 mol L^{-1}). Abbreviation used are s = singlet, d = doublet, t = triplet, q = quartet, sept = septet, m = multiplet, dd = doublet of doublets, ddt = doublet of doublet of triplets, dm = doublet of multiplets, br = broad, br d = broad doublet, br m = broad multiplet. Elemental analyses were performed by the "Service de microanalyses", Université de Strasbourg. The preparations of **PC$_{\text{NHC}}$P** and **Dipp-PC$_{\text{NHC}}$** have been reported before.[6f,h] The precursors [Rh(μ-Cl)(COD)]$_2$,[18] [Rh_2(μ-Cl)Cl(CO)$_4$],[19] [(C_6F_5)BO]$_3$[20] and [Fe_4Cl_8(THF)$_6$][21] were prepared according to the literature.

Synthesis of PC$_{\text{NHC}}$P-RhCl. To a solution of [RhCl(COD)]$_2$ (0.030 g, 0.061 mmol) in THF (5 ml) was added a solution of **PC$_{\text{NHC}}$P** (0.100 g, 0.281 mmol) in THF (5 ml) at room temperature and the reaction mixture was stirred for 2 h. After evaporation of the volatiles, the residue was washed with pentane (20 ml) and dried under vacuum to give a bright yellow powder (0.100 g, 96%). X-ray quality crystals were obtained by slow diffusion of pentane into its CH_2Cl_2 solution. Analysis: Found (Calcd for $C_{38}H_{76}ClN_4P_4Rh$) (%): C, 53.57 (53.61), H, 8.89 (9.00), N, 6.75 (6.58). ^1H NMR (400 MHz, CD_2Cl_2): δ 7.15 (d, 2H, $^3J_{HP}$ = 2.1 Hz, im-*H*), 7.13 (s, 2H, im-*H*), 1.52 (t, 36H, $^3J_{HP}$ = 7.4 Hz, C(C*H*$_3$)$_3$), 1.21 (d, 36H, $^3J_{HP}$ = 12.5 Hz, C(C*H*$_3$)$_3$). $^{13}C\{^1H\}$ NMR (125 MHz, CD_2Cl_2): δ 186.1 (ddt, $^2J_{CP}$ = 53.5 Hz, $^1J_{C–Rh}$ = 40.4 Hz, $^2J_{CP}$ = 11.2 Hz, N*C*N), 124.2 (d, $^2J_{CP}$ = 6.5 Hz, im-*C*), 122.2 (im-*C*), 36.8 (q, $^1J_{CP}$ = 2.0 Hz, *C*(CH$_3$)$_3$), 35.2 (d, $^1J_{CP}$ = 29.6 Hz, *C*(CH$_3$)$_3$), 29.5 (q, $^2J_{CP}$ = 4.5 Hz, C(*C*H$_3$)$_3$), 29.1 (d, $^2J_{CP}$ = 15.7 Hz, C(*C*H$_3$)$_3$). $^{31}P\{^1H\}$ NMR (161 MHz, CD_2Cl_2): δ 113.1 (d, $^1J_{P–Rh}$ = 146.9 Hz), 83.8 (s).

Synthesis of PC$_{\text{NHC}}$-RhCO. To a solution of [Rh_2(μ-Cl)$_2$(CO)$_4$] (0.088 g, 0.226 mmol) in THF (5 ml) was added a solution of **PC$_{\text{NHC}}$P** (0.160 g, 0.449 mmol) in THF (5 ml) at room temperature and the reaction mixture was stirred for 2 h. It was then was concentrated to *ca.* 2 ml and 20 ml pentane were added to precipitate the product. The supernatant was removed by filtration and the solid was dried under vacuum to give a brown powder (0.066 g, 44%). X-ray quality crystals were obtained by slow diffusion of pentane into its THF solution. Analysis: Found (Calcd for $C_{24}H_{40}O_2N_4P_2Rh_2$) (%): C, 42.01 (42.12), H, 5.79 (5.89), N, 8.43 (8.19). ^1H NMR (400 MHz, CD_2Cl_2): δ 7.04 (t, 2H, $^3J_{HP}$ = 1.8 Hz, im-*H*), 6.95 (s, 2H, im-*H*), 1.40 (d, 36H, $^3J_{HP}$ = 15.0 Hz, C(C*H*$_3$)$_3$). $^{13}C\{^1H\}$ NMR (125 MHz, CD_2Cl_2): δ 194.09 (dd, $^1J_{C–Rh}$ = 61.9 Hz, $^2J_{CP}$ = 12.9 Hz, CO), 177.3 (dd, $^1J_{C–Rh}$ = 35.8 Hz, $^2J_{CP}$ = 24.2 Hz, N*C*N), 132.3 (d, $^3J_{CP}$ = 5.3 Hz, im-*C*), 119.4 (d, $^2J_{CP}$ = 7.0 Hz, im-*C*), 37.1 (d, $^1J_{CP}$ = 10.3 Hz, *C*(CH$_3$)$_3$), 28.4 (d, $^2J_{CP}$ = 6.6 Hz, C(*C*H$_3$)$_3$). $^{31}P\{^1H\}$ NMR (161 MHz, CD_2Cl_2): δ 128.4 (d, $^1J_{Rh–P}$ = 142.8 Hz).

Synthesis of PC$_{\text{NHC}}$P-Fe. In the glovebox, 2 ml THF was added at room temperature to a solid mixture of **PC$_{\text{NHC}}$P** (0.020 g, 0.056 mmol) and [Fe_4Cl_8(THF)$_6$] (0.012 g, 0.013 mmol). After it was stirred for 0.5 h, the solution was layered with 10 ml pentane and crystallization for four days yielded colourless and extremely air-sensitive crystals (0.014 g, 67%), which were suitable for X-ray diffraction. Due to the air sensitivity of this complex, satisfactory elemental analyses could not be obtained.

Synthesis of PC$_{\text{NHC}}$P-Se. To a solution of **PC$_{\text{NHC}}$P** (0.050 g, 0.140 mmol) in THF (5 ml) was added a suspension of selenium (0.011 g, 0.139 mmol) in THF (8 ml) at room temperature and the reaction mixture was stirred for 1 h. After evaporation of the solvent to dryness, the residue was washed with pentane (10 ml) and dried under vacuum to give a white powder (0.057 g, 93%). X-ray quality crystals were obtained by slow diffusion of pentane into its THF solution at −30 °C. Analysis: Found (Calcd for $C_{19}H_{38}N_2P_2Se$) (%): C, 52.30 (52.41), H, 8.78 (8.80), N, 6.73 (6.43). ^1H NMR (600 MHz, $CDCl_3$): δ 7.19 (s, im-*H*), 1.25 (d, 36H, $^3J_{HP}$ = 12.4 Hz, C(C*H*$_3$)$_3$). ^1H NMR (400 MHz, CD_2Cl_2): δ 7.18 (s, im-*H*), 1.22 (d, 36H, $^3J_{HP}$ = 12.3 Hz, C(C*H*$_3$)$_3$). $^{13}C\{^1H\}$ NMR (125 MHz, CD_2Cl_2): δ 176.6 (t, $^2J_{CP}$ = 34.3 Hz, N*C*N), 122.6 (t, $^2J_{CP}$ = 4.3 Hz, im-*C*), 35.9 (d, $^1J_{CP}$ = 33.7 Hz, *C*(CH$_3$)$_3$), 29.3 (d, $^2J_{CP}$ = 17.7 Hz, C(*C*H$_3$)$_3$). $^{31}P\{^1H\}$ NMR (243 MHz, $CDCl_3$): δ 91.0 (s). ^{77}Se NMR (114 MHz, $CDCl_3$): δ 166.9 (t, $^2J_{SeP}$ = 46.5 Hz).

Synthesis of Dipp-PC$_{\text{NHC}}$-Se. A synthetic procedure similar to that for **PC$_{\text{NHC}}$P-Se** was applied using **Dipp-PC$_{\text{NHC}}$** (0.050 g, 0.134 mmol) and selenium (0.010 g, 0.127 mmol). Compound **Dipp-PC$_{\text{NHC}}$-Se** was obtained as a white powder (0.055 g, 92%). Analysis: Found (Calcd for $C_{23}H_{37}N_2PSe$) (%): C, 61.01 (61.19), H, 8.20 (8.26), N, 6.41 (6.20). ^1H NMR (600 MHz, $CDCl_3$): δ 7.44 (t, 1H, $^3J_{HH}$ = 7.7 Hz, Ar–*H*), 7.31 (dd, 1H, $^3J_{HH}$ = 2.1 Hz, $^4J_{HP}$ = 0.3 Hz, im-*H*), 7.26 (d, 2H, $^3J_{HH}$ = 7.7 Hz, Ar–*H*), 6.87 (dd, 1H, $^3J_{HH}$ = 2.1 Hz, $^3J_{HP}$ = 1.3 Hz, im-*H*), 2.50 (sept, 2H, $^3J_{HH}$ = 6.9 Hz, iPr-C*H*), 1.32 (d, 18H, $^3J_{HP}$ = 12.5 Hz, C(C*H*$_3$)$_3$), 1.28 (d, 6H, $^3J_{HH}$ = 6.9 Hz, iPr-C*H*$_3$), 1.10 (d, 6H, $^3J_{HH}$ = 6.9 Hz, iPr-C*H*$_3$). $^{13}C\{^1H\}$ NMR (125 MHz, $CDCl_3$): δ 169.1 (d, $^2J_{CP}$ = 36.1 Hz, N*C*N), 146.1 (Ar–*C*), 134.9 (Ar–*C*), 130.2 (Ar–*C*H), 124.4 (Ar–*C*H), 122.0 (d, $^2J_{CP}$ = 7.6 Hz, im-*C*), 121.7 (d, $^3J_{CP}$ = 1.3 Hz, im-*C*), 35.9 (d, $^1J_{CP}$ = 33.1 Hz, *C*(CH$_3$)$_3$), 29.3 (d, $^2J_{CP}$ = 17.5 Hz, C(*C*H$_3$)$_3$), 29.0 (iPr-*C*H), 24.6 (iPr-*C*H$_3$), 23.5 (iPr-*C*H$_3$). $^{31}P\{^1H\}$ NMR (243 MHz, $CDCl_3$): δ 90.5 (s). ^{77}Se NMR (114 MHz, $CDCl_3$): δ 131.1 (d, $^2J_{SeP}$ = 40.0 Hz).

Synthesis of PC$_{\text{NHC}}$P-B1. To a solid mixture of free carbene **PC$_{\text{NHC}}$P** (0.035 g, 0.098 mmol) and B(C_6F_5)$_3$ (0.051 g, 0.100 mmol) was added 3 ml toluene at room temperature and the reaction mixture was stirred for 2 h. After removal of the supernatant by filtration, the residue was washed with pentane (10 ml) and dried under reduced pressure to give a white powder (0.075 g, 87%). X-ray quality crystals were obtained by slow diffusion of pentane into its THF solution. Due to the sensitivity to air, satisfactory elemental analyses could not be obtained. ^1H NMR (400 MHz, *d*^{8}-THF): δ 7.69 (s, 2H, im-*H*), 1.26 (d, 18H, $^3J_{HP}$ = 13.1 Hz, C(C*H*$_3$)$_3$), 1.01 (d, 18H, $^3J_{HP}$ = 12.9 Hz, C(C*H*$_3$)$_3$). $^{13}C\{^1H\}$ NMR (125 MHz, *d*^{8}-THF): δ 177.1 (br m, N*C*N), 149.9 (br d, $^1J_{CF}$ = 235.2 Hz, *o*-Ar*C*F), 140.4 (br d, J_{CF} = 244.0 Hz, *p*-Ar*C*F), 137.5 (br d, $^1J_{CF}$ = 238.0 Hz, *m*-Ar*C*F), 128.1 (im-*C*), 123.6 (br, Ar*C*B), 37.0 (d, $^1J_{CP}$ = 30.1 Hz, *C*(CH$_3$)$_3$), 36.7 (d, $^1J_{CP}$ = 31.1 Hz, *C*(CH$_3$)$_3$), 29.4 (d, $^2J_{CP}$ = 18.3 Hz, C(*C*H$_3$)$_3$), 29.0 (d, $^2J_{CP}$ = 18.5 Hz, C(*C*H$_3$)$_3$). $^{31}P\{^1H\}$ NMR (161 MHz, *d*^{8}-THF): δ 110.5 (br). ^{11}B NMR (128 MHz, *d*^{8}-THF): δ −17.5 (s). ^{19}F NMR (564 MHz, d^8-THF): δ −122.0 (br, 2F, *o*-Ar*CF*), −125.5 (br, 2F, *o*-Ar*CF*), −132.1 (br, 2F, *o*-Ar*CF*), −162.6 (br, 4F, *p*-Ar*CF*), −168.2 (br, 2F, *m*-Ar*CF*), −168.7 (br, 3F, *p*-Ar*CF*), −169.1 (br, 2F, *m*-Ar*CF*).

Synthesis of PC$_{NHC}$P-B2. To a suspension of $[(C_6F_5)BO]_3$ (0.116 g, 0.199 mmol) in toluene (2 ml) was added a solution of **PC$_{NHC}$P** (0.072 g, 0.202 mmol) in toluene (2 ml) at room temperature and stirring was maintained for 1 h. The reaction mixture was concentrated to 2 ml and 20 ml pentane was added to precipitate the product. After filtration, the residue was dried under reduced pressure to give a white powder (0.120 g, 64%). X-ray quality crystals were obtained by cooling down its toluene solution to −30 °C for two days. Analysis: Found (Calcd for $C_{37}H_{38}B_3F_{15}N_2O_3P_2$) (%): C, 47.72 (47.37), H, 4.17 (4.08), N, 2.97 (2.99). ^{1}H NMR (400 MHz, d^8-THF): δ 7.66 (s, 2H, im-*H*), 1.15 (d, 36H, $^3J_{HP}$ = 12.9 Hz, C(C*H*$_3$)$_3$). ^{13}C{^{1}H} NMR (125 MHz, d^8-THF): δ 175.9 (br, N*C*N), 149.9 (dm, $^1J_{CF}$ = 249.7 Hz, *o*-Ar*C*F), 148.7 (dm, $^1J_{CF}$ = 241.6 Hz, *o*-Ar*C*F-BC$_{NHC}$), 142.8 (dm, J_{CF} = 255.3 Hz, *p*-Ar*C*F), 140.3 (dm, $^1J_{CF}$ = 241.4 Hz, *p*-Ar*C*F-BC$_{NHC}$), 137.8 (dm, $^1J_{CF}$ = 250.7 Hz, overlapping *m*-Ar*C*F and *m*-Ar*C*F-BC$_{NHC}$), 126.0 (im-*C*), 124.9 (br, Ar*C*B), 109.7 (br, Ar*C*B–C$_{NHC}$), 35.9 (d, $^1J_{CP}$ = 35.2 Hz, *C*(CH$_3$)$_3$), 29.0 (d, $^2J_{CP}$ = 17.7 Hz, C(*C*H$_3$)$_3$). ^{31}P{^{1}H} NMR (161 MHz, d^8-THF): δ 97.6 (s). ^{11}B NMR (128 MHz, d^8-THF): δ 26.4 (br, Ar*B*), −0.6 (s, Ar*B*–C$_{NHC}$). ^{19}F NMR (282 MHz, d^8-THF): δ −132.4 (dm, 4F, $^3J_{FF}$ = 22.4 Hz, *o*-ArC*F*), −135.3 (m, 2F, *o*-ArC*F*-BC$_{NHC}$), −156.0 (tt, 2F, $^3J_{FF}$ = 20.0 Hz, $^4J_{FF}$ = 3.1 Hz, *p*-ArC*F*), −164.0 (t, 1F, $^3J_{FF}$ = 20.3 Hz, *p*-ArC*F*-BC$_{NHC}$), −166.1 (m, 4F, *m*-ArC*F*), −168.5 (m, 2F, *m*-ArC*F*-BC$_{NHC}$).

X-ray crystallography

Summary of the crystal data, data collection and refinement for the structures of **PCP-RhCl**·2CH$_2$Cl$_2$, **PC$_{NHC}$-RhCO**, **PC$_{NHC}$P-Fe**, **PC$_{NHC}$P-Se**, **PC$_{NHC}$P-B-1**·THF and **PC$_{NHC}$P-B-2**·toluene are given in Table S1.†

For **PC$_{NHC}$P-RhCl**·2CH$_2$Cl$_2$, **PC$_{NHC}$P-Fe**, **PC$_{NHC}$P-Se**, **PC$_{NHC}$P-B-1**·THF and **PC$_{NHC}$P-B-2**·toluene, X-ray diffraction data collection was carried out on a Bruker APEX II DUO Kappa-CCD diffractometer equipped with an Oxford Cryosystem liquid N$_2$ device, using Mo-Kα radiation (λ = 0.71073 Å). The crystal-detector distance was 38 mm. The cell parameters were determined (APEX2 software)[22] from reflections taken from three sets of 12 frames, each at 10s exposure. The structure was solved by direct methods using the program SHELXS-97.[23] The refinement and all further calculations were carried out using SHELXL-97.[24] The H-atoms were included in calculated positions and treated as riding atoms using SHELXL default parameters. The non-H atoms were refined anisotropically, using weighted full-matrix least-squares on F^2. A semi-empirical absorption correction was applied using SADABS in APEX2.[22]

For **PC$_{NHC}$-RhCO**, X-ray diffraction data collection was carried out on a Nonius Kappa-CCD diffractometer equipped with an Oxford Cryosystem liquid N$_2$ device, using Mo-Kα radiation (λ = 0.71073 Å). The crystal-detector distance was 36 mm. The cell parameters were determined (Denzo software)[25] from reflections taken from one set of 10 frames (1.0° steps in phi angle), each at 20 s exposure. The structures were solved by direct methods using the program SHELXS-97.[23] The refinement and all further calculations were carried out using SHELXL-97.[24] The H-atoms were included in calculated positions and treated as riding atoms using SHELXL default parameters. The non-H atoms were refined anisotropically, using weighted full-matrix least-squares on F^2. A semi-empirical absorption correction was applied using MULscanABS in PLATON.[26]

Conflict of interest

The authors declare no competing financial interest.

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