A convenient method for the generation of \{\text{Rh(PNP)}\}^+ and \{\text{Rh(PONOP)}\}^+ fragments: reversible formation of vinylidene derivatives†

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The substitution reactions of \([\text{Rh(COD)}_2][\text{BArF}_4]\) with PNP and PONOP pincer ligands 2,6-bis(di-tert-butylphosphinomethyl)pyridine and 2,6-bis(di-tert-butylphosphinito)pyridine in the weakly coordinating solvent 1,2-F_2C_6H_4 are shown to be an operationally simple method for the generation of reactive formally 14 VE rhodium(I) adducts in solution. Application of this methodology enables synthesis of known adducts of CO, N_2, H_2, previously unknown water complexes, and novel vinylidene derivatives \([\text{Rh(pincer)}(\text{CCHR})][\text{BArF}_4]\) \((R = \text{tBu}, 3,5-\text{tBu}_2C_6H_3)\), through reversible reactions with terminal alkynes.

Introduction

Phosphine-based pinners are a prominent ligand class in contemporary organometallic chemistry and catalysis, conferring thermal stability whilst permitting a wide range of metal-based reactivity.1-3 From a fundamental perspective, their capacity to support the generation of reactive low-coordinate metal fragments provides an attractive framework for gaining insights into the mechanism of small molecule activation reactions. The synthesis and characterisation of a rhodium(I) σ-methane complex in solution is a particularly outstanding example, with direct mechanistic relevance to C(sp^3)–H bond activation and alkane dehydrogenation processes mediated at iridium homologues.5,6 Other group 9 highlights include the C(sp^3)–H bond oxidative addition of aryl halides4,5 and the selective C(sp^3)–F bond activation of fluorocarbons.6 In the context of supporting such endeavours and building on preceding work (Scheme 1),4-7,9 we herein report a convenient method for accessing reactive formally 14 VE rhodium(I) adducts of the widely studied PNP (2,6-bis(di-tert-butylphosphinomethyl)pyridine) and PONOP (2,6-bis(di-tert-butylphosphinito)pyridine) ligands, exploiting metastable coordination of 1,5-cyclooctadiene (COD) in the weakly coordinating 1,2-difluorobenzene solvent (DFB).10 We showcase this methodology for the preparation of previously unknown water complexes and the reversible formation of vinylidene derivatives.

Results and discussion

As an operationally simple entry point into the organometallic chemistry of cationic rhodium(i) pincer complexes, we targeted substitution reactions of the readily accessible (and commercially available) rhodium precursor \([\text{Rh(COD)}_2][\text{BArF}_4]\) \((\text{ArF} = 3,5-(\text{CF}_3)_2C_6H_3)\); postulating that alongside chelation of the pincer, steric buttressing from the phosphine substituents would promote efficient liberation of the comparatively bulky COD ligand and access to reactive \{\text{Rh}(\text{pincer})\}^+ fragments in solution.11 To this end, stoichiometric reactions between PNP/ PONOP and \([\text{Rh(COD)}_2][\text{BArF}_4]\) in DFB under an argon atmosphere were first studied \textit{in situ}, resulting in quantitative coordination of the pincer and establishment of dynamic equilibrium mixtures containing monomeric \(1\) (PNP, \(\delta_{\text{H}}^\text{PP} 63.4, 52.6, ^2J_{\text{PP}} \sim 320 \text{ Hz})\); PONOP, \(\delta_{\text{H}}^\text{PP} 202.5, ^2J_{\text{PP}} = 134 \text{ Hz}) as

Scheme 1 Latent sources of the \{\text{Rh(PNP)}\}^+ and \{\text{Rh(PONOP)}\}^+ fragments (X = O, CH_2). COE = cyclooctene; COD = 1,5-cyclooctadiene.
the major components and dimeric 1b as the minor components, alongside liberated COD (Scheme 2). The former were formed exclusively when the reactions were repeated in the presence of 10 equivalents of COD, while the latter dications were isolated in high yield by crystallisation from DFB/hexane [PNP, 90%; PONOP, 96%], structurally characterised in the solid state using X-ray diffraction and the bulk purity established by microanalysis (see Fig. 1 for 1b-O).† The synthetic utility of this methodology was then assessed by reacting mixtures of 1a/b, generated as described above in DFB, with CO, H2, and N2 (1 atm) and analysis in situ using 1H and 31P NMR spectroscopy. Introduction of strongly coordinating CO readily apparent due to their striking deep green colours. Both complexes were subsequently isolated from solution and fully characterised in solution and the solid state.† The NMR spectra of 3a/b-CH2 are notable for the presence of vinylidene 13C resonances at δ 317.5/326.9 (located by HMBC experiments), time-averaged G2v symmetry – reconciled by free

Application of our methodology allows access to novel rhodium(i) pincer adducts of water 2d. PNP variant 2d-CH2 (δpp 63.1, JRhP = 144 Hz) was formed quantitatively on addition of excess degassed water (40 equiv.) to an equilibrium mixture of 1a/b-CH2 generated from stoichiometric reaction between [Rh(COD)2][BARF4] and PNP in DFB (t ~ 3 h). Consistent with the aforementioned reactivity trends PONOP variant 2d-O (δpp 199.1, JRhP = 150 Hz) was, however, only formed with 88% conversion after 3 days under these conditions. Analytically pure samples of the 2d-CH2 (71% yield) and 2d-O (49% yield) were obtained using 1a/b-CH2 or 1b-O, respectively, and excess water (500 equiv./Rh). The structural formulation of both new aqua complexes was confirmed using a combination of NMR spectroscopy, X-ray diffraction (see Fig. 1 for 2d-O) and satisfactory microanalysis. The solid-state structures of 2d are notable for and Rh–OH2 bond lengths of ca. 2.15 Å and the presence of an additional hydrogen bonded water molecule in the lattice (RhOH2⋯OH2 = 2.7–2.8 Å).11

As a means of showcasing our new methodology and as part of our work exploring C(sp)–H activation reactions mediated by cationic rhodium(i) pinners,14 we set about studying the reactivity of the associated {Rh(pincer)}+ fragments with two bulky terminal alkynes (Scheme 3). Using isolated 1b-CH2 as the precursor, reaction with both HCCBu and HCCAr′ (Ar′ = 3,5-tBu2C6H3) in DFB under an argon atmosphere resulted in rapid (t < 5 min) and quantitative formation of vinylidene derivatives 3a/b-CH2, the formation of which was readily apparent due to their striking deep green colours. Both complexes were subsequently isolated from solution and fully characterised by free

Fig. 1 Solid-state structures of 1b-O and 2d-O. Thermal ellipsoids drawn at 50% probability; anions and most hydrogen atoms omitted for clarity. The starred atoms are generated using the symmetry operation –x, 1 – y, 1 – z. Selected bond lengths (Å): 1b-O: Rh1–Cnt(C4, C5), 2.083(2); cf. 1b-CH2, Rh1–Cnt(C4, C5), 2.058(2); 2d-O: Rh1–O4, 2.154(2); cf. 2d-CH2, 2.152(7).
rotation about the Rh–C=C vector – and single phosphorus resonances with large coupling to $^{103}$Rh ($\delta_{\text{RhP}}$ 65.6/65.9, $J_{\text{RhP}}$ = 139/137 Hz). The solid-state structures affirm the structural assignments and, in addition to the Rh=C bond lengths of 1.81–1.84 Å that are fully inline with related rhodium precursors, notable for the adoption of both 3a-O and 3b-CH$_2$ symmetric pincer ligand conformations; demonstrating the flexibility of lutidene-based pincer backbones. In a similar manner, deep blue vinylidene formations; demonstrating the flexibility of lutidene-based graphic occupancies precluded separation in this manner.

Curiously, we note reaction of isolated 3a-O with CO (1 atm) resulted in complete conversion to 2a in all cases with concomitant liberation of the corresponding terminal alkynes (t < 90 min). Such reversible vinylidene formation is well documented in ruthenium complexes, and in line with related observations we have made when studying C(sp)$^2$–H bond activation reactions of cationic rhodium complexes of NHC-based pincer ligands.

**Conclusions**

We have demonstrated that reaction between the readily accessible (and commercially available) rhodium precursor $[\text{Rh(COD)}_2][\text{BArF}_4]$ and two phosphine-based pincer ligands (2,6-bis(di-tert-butylphosphinomethyl)pyridine and 2,6-bis(di-tert-butylphosphinino)pyridine) in 1,2-F$_2$C$_6$H$_4$ provides a operationally simple method for generating the corresponding $[\text{Rh(pincer)}]^+ \cdot$ fragments, and subsequent synthesis of adducts of CO, H$_2$, N$_2$ and H$_2$O (2). This methodology is underpinned by reversible binding of COD, that leads to dynamic equilibrium mixtures of monomeric $[\text{Rh(pincer)}](\text{COD})[\text{BArF}_4]$ 1a and dimeric $[\text{Rh(pincer)}](\mu$-$\eta^2$-COD)[BArF$_4$] 1b, the latter of which were readily isolated by recrystallisation. This methodology was used to study the reaction between $[\text{Rh(pincer)}]^+$ and bulky terminal alkynes, which resulted in the (reversible) formation of novel vinylidene derivatives $[\text{Rh(pincer)}](\text{CCHR})[\text{BArF}_4]$ [R = tBu, 3a; 3,5-tBu$_2$C$_6$H$_3$, 3b].

**Conflicts of interest**

There are no conflicts to declare.

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**References**

This approach notably avoids the need for a late stage halogen abstraction step, which can limit the choice of regents or solvents. For instance, Na[BArF$_4$] is not a very effective chloride abstractor in DFB due to appreciable solubility of NaCl (see ref. 10). Silver salts are also sufficiently oxidising to enact one electron oxidation of rhodium(I) complexes (see: M. Feller, E. Ben-Ari, T. Gupta, L. J. W. Shimon, G. Leitus, Y. Diskin-Posner, L. Weiner and D. Milstein, Inorg. Chem., 2007, 46, 10479–10490.).


17 These complexes are presumably in equilibrium (and this suggestion is support by subsequent reaction with CO). See: Y. Wakatsuki, J. Organomet. Chem., 2004, 689, 4092–4109.

18 Due to presence as the minor disordered component in the solid state, the metrics associated with the vinylidene in 3b-O are unreliable.