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 [Rh(COD)]2[BF4]2 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-F2C6H4 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, N2, H2, previously unknown water complexes, and novel vinylidene derivatives [Rh(pincer)(CCHR)][BF4]2 (R = tBu, 3,5-tBu2C6H3), through reversible reactions with terminal alkynes.

Introduction

Phosphine-based pincers are a prominent ligand class in contemporary organometallic chemistry and catalysis, conferring thermal stability whilst permitting a wide range of metal-based reactivity.1,2 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(sp3)–H bond activation and alkane dehydrogenation processes mediated at iridium homologues.3,4 Other group 9 highlights include the C(sp3)–H bond oxidative addition of aryl halides5,6 and the selective C(sp3)–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 [Rh(COD)]2[BF4]2 to [Rh(COD)]2[BF4]2 (ArF = 3,5-(CF3)2C6H3); 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(pincer)}\}^+ fragments in solution.11 To this end, stoichiometric reactions between PNP/ PONOP and [Rh(COD)]2[BF4]2 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 1a (PNP, δP 63.4, 52.6, JPP 320 Hz; PONOP, δP 202.5, JPP = 134 Hz) as
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 resulted in rapid (t < 5 min) and quantitative formation of the known carbonyl complexes 2a, with only free COD as the by-product.7,8 Reactions of H2 and N2 with 1a/b likewise afforded the corresponding (known) adducts 2b (with concomitant hydrogenation of COD) and 2c,7,8,12 respectively, but under dis-parately longer timeframes for the PONOP (t ~ 2 days) compared to PNP complexes (t < 3 h). These reactions all proceeded to completion with the exception of 2c-O (ca. 95%), which instead required use of isolated 1b-O to presumably counter recoordination of COD (t ~ 2 days).

Application of our methodology allows access to novel rhodium(i) pincer adducts of water 2d. PNP variant 2d-CH2 (δ19P 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) pincers,14 we set about studying the reactivity of the associated {Rh(pincer)}+ fragments with two bulky terminal alkyne (Scheme 3). Using isolated 1b-CH3 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 in solution and the solid state.† The NMR spectra of 3a/b-CH3 are notable for the presence of vinylidene 13C resonances at δ 317.5/326.9 (located by HMBC experiments), time-averaged C2v symmetry – reconciled by free
rotation about the Rh–C=C vector – and single phosphorus resonances with large coupling to \( ^{103} \text{Rh} \) (\( \delta_{\text{Rh}}^{\text{P}} = 65.6/65.9, J_{\text{RhP}} = 139/137 \) 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 precedents,\(^{15}\) notable for the adoption of both \( C_2 \) (3a-CH\(_2\), \( Z = 2 \)) and \( C_6 \) (3a-CH\(_2\), \( Z = 2; 3b-CH_2 \)) symmetric pincer ligand conformations; demonstrating the flexibility of lutidene-based pincer backbones.\(^{16}\) In a similar manner, deep blue vinylidene complex 3a-O was obtained from HCC\(_2\)Bu and 1b-O, but over a more protracted time frame than the PNP analogue (ca. 18 h; \( \delta_{\text{Rh}}^{\text{P}} = 206.5, J_{\text{RhP}} = 144 \) Hz, \( \delta_{\text{RC}} \) (RhC) 330.0, \( C_2n \) solution symmetry; Fig. 2). Consistent with the aforesaid trends, the reaction between \{Rh(PONOP)\}\(^+\) and HCCAr\(^+\) only resulted in the formation of the green vinylidene derivative 3b-O (\( \delta_{\text{Rh}}^{\text{P}} = 208.4, J_{\text{RhP}} = 143 \) Hz, \( \delta_{\text{RC}} \) (RhC) 339.5) as the minor component (30\%) of a mixture with the balance made up by the corresponding \( \pi \)-complex \{Rh(PONOP)(HCCAr)][(BARF)\(_4\]) (2e-O; \( \delta_{\text{Rh}}^{\text{P}} = 194.6, J_{\text{RhP}} = 129 \) Hz).\(^{17}\) This ratio was found even in use of excess alkyne and the co-crystallisation of these two compounds (with the ratio reflected in the corresponding crystallographic occupancies) precluded separation in this manner.\(^{18}\)

Curiously, we note reaction of isolated 3 (in the case of 3b-O, as a mixture with 2e-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,\(^{19}\) and in line with related observations we have made when studying C(sp)–H bond activation reactions of cationic rhodium complexes of NHC-based pincer ligands.\(^{14}\)

**Conclusions**

We have demonstrated that reaction between the readily accessible (and commercially available) rhodium precursor [Rh(COD)]\(_2\)[BARF]\(_4\]) and two phosphine-based pincer ligands (2,6-bis(di-tert-butylphosphinomethyl)pyridine) and 2,6-bis(diter-tert-butylphosphino)pyridine) in 1,2-F\(_2\)C\(_6\)H\(_4\) provides a operationally simple method for generating the corresponding \{Rh(pincer)]\(^+\) 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 equilibriums of monomeric [Rh(pincer)][\( \eta^2 \)-COD][BARF]\(_4\]) 1a and dimeric \{[Rh(pincer)]\(_2\)[\( \mu-\eta^2\eta^2\)-COD][BARF]\(_4\] 1b, the latter of which were readily isolated by recrystallisation. This methodology was used to study the reaction between \{Rh(pincer)]\(^+\) and bulky terminal alkynes, which resulted in the (reversible) formation of novel vinlylidene derivatives \{Rh[pincer][CCHR]][BARF]\(_4\]) (\( R = \text{Bu}, 3a; 3,5\)-tBu_2C\(_6\)H\(_3\), 3b).

**Conflicts of interest**

There are no conflicts to declare.

**Acknowledgements**

We thank the European Research Council (ERC, grant agreement 637313) and Royal Society (UF100592, UF150675, A. B. C.) for financial support. Crystallographic data for 3a-O were collected using an instrument purchased through support from Advantage West Midlands and the European Regional Development Fund. All other crystallographic data were collected using an instrument that received funding from the ERC under the European Union’s Horizon 2020 research and innovation programme (grant agreement no. 637313).

**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, \textit{Inorg. Chem.}, 2007, \textbf{46}, 10479–10490).


17 These complexes are presumably in equilibrium (and this suggestion is support by subsequent reaction with CO). See: Y. Wakatsuki, \textit{J. Organomet. Chem.}, 2004, \textbf{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.