

XBphos-Rh: A Halogen-Bond Assembled Supramolecular Catalyst†

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The use of halogen bonding as a tool to construct the catalyst backbone is reported. Specifically, pyridyl- and iodotetrafluoroaryl-substituted phosphines were assembled in the presence of a rhodium(I) precursor to form the corresponding halogen-bonded complex **XBphos-Rh**. The presence of fluorine substituents at the iodo-containing supramolecular motif was not necessary for halogen bonding to occur due to the template effect exerted by the rhodium center during formation of the halogen-bonded complex. The halogen-bonded supramolecular complexes were successfully tested in the catalytic hydroboration of terminal alkynes.

Introduction

The evolution of metal-based homogeneous catalysis has run in parallel with the development of structurally diverse ligands.¹ Ligand design allows the behaviour of the metal centre to be influenced and its catalytic activity and selectivity to be modified.

Supramolecular chemistry has emerged as a more efficient tool for the construction of (enantiopure) ligand backbones of metal complexes when compared with standard covalent chemistry. Supramolecular strategies mainly rely on the self-assembly of building blocks that contain both the complementary motifs required for the assembly, and the binding groups necessary for the desired catalysis event. This approach has been successfully employed for preparing catalysts by assembling supramolecularly complementary building blocks through hydrogen-bonding, metal-ligand, or ionic interactions.² However, the use of halogen bonding for constructing the backbone of a catalyst remains, to the best of our knowledge, unexplored.³

The directionality and strength of halogen bonding,⁴ together with a greater tolerance to solvent polarity changes,⁵ prompted us to design and develop new halogen-bonded metal catalysts (see Scheme 1). We speculated that the halogen bonding-mediated assembly of two appropriate building blocks, each bearing a ligating group, could lead to the formation of a metal complex due to the chelation effect that should be exhibited in the presence of the metal centre. With regard to the ligating groups, we focused our attention on phosphino groups due to their pre-eminence in homogeneous catalysis⁶ and their tolerance to functionalisation.⁷ With

respect to the halogen bonding motifs, we envisaged that the use of a fluorinated iodoarene and a pyridine group could be suitable due to the reported complementarity of both supramolecular motifs.⁸ Concerning the metal centre, we focused on rhodium as its complexes are catalytically active in pivotal organic transformations. In the discussion that follows, we report our results in the preparation and full characterisation of the first examples of halogen-bonded rhodium(I) complexes and their catalytic performance in alkyne hydroborations.

Results and discussion

Examination of CPK models revealed that the relative arrangements of the P-ligating groups and the halogen bond acceptor and donor motifs in 2-pyridyldiphenylphosphine (**1**) and 2-iodo-3,4,5,6-tetrafluorophenyldiphenylphosphine (**2**), respectively, were adequate for the formation of the target halogen-bonded Rh(I) complex (see Scheme 2). Building blocks **1** and **2** were successfully prepared in good yields in a multigram scale by slight modification of well-established synthetic protocols.⁹ We envisaged that the use of [Rh(Cl)(CO)₂]₂ along with a halide scavenger would render a putative [Rh(CO)₂]X intermediate that should react with phosphines **1** and **2**. After some experimentation, halogen-bonded rhodium(I) complexes were obtained by first reacting [Rh(Cl)(CO)₂]₂ and NaBARf,¹⁰ and then adding ligands **1** and **2** as indicated in Scheme 2.¹¹ The structure of the complex was confirmed by standard spectroscopic studies. The ³¹P{¹H} NMR

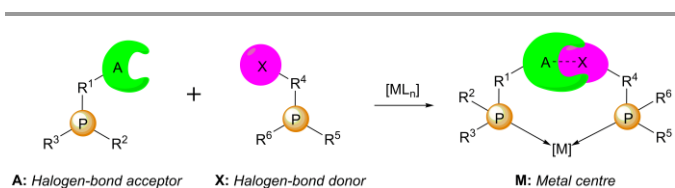
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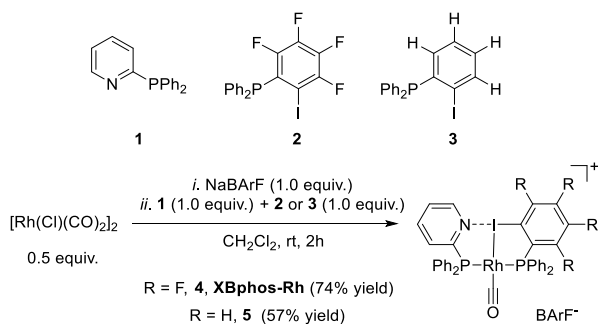
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Scheme 1 Supramolecular halogen-bonded catalysts (A: halogen bond acceptor; X: halogen bond donor; M: metal centre).



Scheme 2 Synthesis of halogen-bonded rhodium(I) chelates.

spectrum showed two complex multiplets, from which a high value $^2J_{\text{P-P}}$ coupling constant (i.e. 276 Hz; unequivocally assigned by 2D $^{31}\text{P}\{^1\text{H}\}$ J -resolved spectroscopy; Fig. SI 52 ESI[†]) was calculated. According to the literature reviewed, this high value $^2J_{\text{P-P}}$ coupling constant indicates a *trans*-spanning bisphosphine coordinated to the rhodium centre.¹² We initially expected a dicarbonyl complex, but ESI-MS analysis identified complex $[\text{Rh}(\text{CO})(\mathbf{1})(\mathbf{2})]\text{BARf}$ (**4**), referred to as **XBphos-Rh**¹³ in the discussion that follows.

X-ray analysis confirmed the proposed halogen-bonded structure of the rhodium complex derived from **1** and **2** (see Scheme 2 for the structure of **XBphos-Rh** and Fig. 1A for the crystal structure). The nitrogen and iodine are aligned with a N–I distance of 2.757(8) Å and with a N···I–C bond angle of 169.4(5)°. These structural parameters are in agreement with those reported for halogen-bonded complexes involving pyridine and fluorinated iodoaryl moieties.¹⁴ Interestingly, the iodine appears to be coordinated to the rhodium centre (Rh–I distance = 2.5535(7) Å). Thus, the tridentate coordination of the halogen-bonded ligands in square planar **XBphos-Rh** resembles that observed in pincer-type complexes,¹⁵ and therefore this complex can be formally considered as the first reported P–I–P pincer-type complex.

Given the favourable template effect exerted by the rhodium centre on the coordinated atoms in **XBphos-Rh**, we envisaged that fluorine-free compound **3** could also be used as the halogen bond donor. Thus, complex **5** could be prepared in good yields following a synthetic protocol analogous to that employed for **XBphos-Rh** (Scheme 2). Crystals from **5** suitable for X-ray analysis confirmed the proposed structure for the rhodium complex derived from **1** and **3** (Scheme 2 and Fig. 1B).

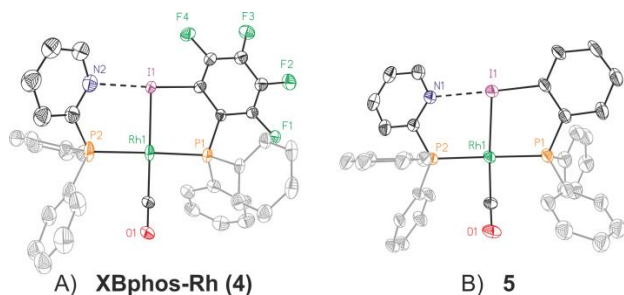


Fig. 1 Crystal structures of **XBphos-Rh** (A) and **5** (B). Hydrogen atoms and the BARf unit have been omitted for the sake of clarity. Colour scheme: C: black, P: orange, Rh: green, F: green, N: blue, I: purple, O: red. Atomic displacement ellipsoids are drawn at a 50% probability.

The analysis of the solid-state structures revealed a longer N–I distance for **5** than for **XBphos-Rh** (2.84(1) Å for **5** and 2.757(8) Å for **4**), which indicates a stronger halogen bond interaction in the fluorine-containing complex.

The formation of a halogen bonding interaction between the pyridine and iodoarene motifs is driven by an enthalpy gain but penalised by an entropic unfavourable contribution arising from the geometry constraints for effective bonding (i.e. linear arrangement of the N···I–C atoms). Overall, the free energy associated with a single interaction is low.¹⁶ In order to gain a deeper insight into the halogen bonding event, full level DFT calculations were carried out. Geometries and stabilities of $[\text{Rh}(\text{CO})(\mathbf{1})(\mathbf{2})]^+$ and $[\text{Rh}(\text{CO})(\mathbf{1})(\mathbf{3})]^+$ and those of the starting building blocks were computed with Gaussian 09¹⁷ with the TPSS¹⁸-D3¹⁹ density functional employing a medium-sized triple-zeta (def2TZVP²⁰) basis set, which is a good compromise between the computational cost and the reliability in describing halogen bonding.²¹ Selected geometrical parameters and computed binding free energies are summarised in Table 1. To aid comparison, the supramolecular interaction between 4MePy and IPFB (see footnote a in Table 1 for the abbreviations) was also computed and was found to be a slightly endergonic process with a calculated binding constant value being in agreement with that experimentally measured (i.e.; $K_{\text{exp}} = 1 \pm 1 \text{ M}^{-1}$ in toluene in ref. 16 and $K_{\text{calc}} = 0.03 \text{ M}^{-1}$ from the predicted $\Delta\Delta\text{G}$ value in entry 1 in Table 1). The computed N–I distances were in agreement with the experimental values and their formations were calculated to be highly exergonic processes. Computational studies confirmed a slightly higher stability for $[\text{Rh}(\text{CO})(\mathbf{1})(\mathbf{2})]^+$ than for $[\text{Rh}(\text{CO})(\mathbf{1})(\mathbf{3})]^+$ (entries 2 and 3, Table 1). Electrostatic potential surfaces were calculated at the level of theory described above (see Fig. 2 for **2** and $[\text{Rh}(\text{CO})(\mathbf{1})(\mathbf{2})]^+$ and ESI for all information). The maximum values of the σ -hole in **2** (Figure 2) and fluorine-free derivative **3** (ESI) are 25.1 and 12.5 kcal·mol⁻¹, respectively. A lower σ -hole value indicates a lower donor character of the halogen atom to the supramolecular bond. This observation derived from electrostatic potentials is in agreement with previously discussed X-ray data (i.e. a longer N–I bond for **5** than for **XBphos-Rh**).

The interesting structural features of **XBphos-Rh** and **5** (Table 2),²² prompted us to investigate reactivity features as catalysts

Table 1 Selected geometrical parameters for halogen-bonded complexes (TPSS-D3/def2TZVP, 298 K, toluene) and computed binding free energies.

Entry	Complex	$d_{\text{N-I}}$ (Å)	N···I–C bond angle (°)	$\Delta\Delta\text{G}$ (kcal·mol ⁻¹)
1	4MePy-IPFB ^a	2.714	179.4	+2.03 ^b
2 ^c	$[\text{Rh}(\text{CO})(\mathbf{1})(\mathbf{2})]^+$	2.709 (2.757(8))	175.2 (169.4(5))	–112.83 ^d
3 ^c	$[\text{Rh}(\text{CO})(\mathbf{1})(\mathbf{3})]^+$	2.827 (2.84(1))	176.2 (171.2(7))	–111.97 ^d

^a 4MePy-IPFB = complex between 4-methylpyridine and iodopentafluorobenzene. ^b $\Delta\Delta\text{G} = \Delta\text{G}_{4\text{MePy-IPFB}} - \Delta\text{G}_{4\text{MePy}} - \Delta\text{G}_{\text{IPFB}}$. ^c X-ray values in parentheses. ^d $\Delta\Delta\text{G} = \Delta\text{G}_{[\text{Rh}(\text{CO})(\mathbf{1})(\mathbf{2})]^+} + \Delta\text{G}_{\text{CO}} - \Delta\text{G}_{[\text{Rh}(\text{CO})_2]^+} - \Delta\text{G}_1 - \Delta\text{G}_2$ or 3.

outcome of the reaction,²⁷ application of this system to other catalytically relevant transformations, extension of the application of this halogen bonding approach to other transition metals, and studies into alternative ligand designs.

Conflicts of interest

There are no conflicts to declare.

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