Modulation of σ-Alkane Interactions in [Rh(L\textsubscript{2})(alkane)]\textsuperscript{+} Solid-State Molecular Organometallic (SMOM) Systems by Variation of the Chelating Phosphine and Alkane: Access to \(\eta^2,\eta^2\)-σ-Alkane Rh(I), \(\eta^1\)-σ-Alkane Rh(III) Complexes, and Alkane Encapsulation

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\textbf{ABSTRACT:} Solid/gas single-crystal to single-crystal (SC–SC) hydrogenation of appropriate diene precursors forms the corresponding σ-alkane complexes \([\text{Rh}(\text{Cy}_2\text{P}(\text{CH}_2)_3\text{PCy}_2)(\text{L})]\text{[BArF}_4\text{]} (n = 3, 4) and \([\text{RhH}(\text{Cy}_2\text{P}(\text{CH}_2)_2(\text{CH})-(\text{CH}_2)_2\text{PCy}_2)(\text{L})]\text{[BArF}_4\text{]} (n = 5, L = norbornane, NBA; cyclooctane, COA). Their structures, as determined by single-crystal X-ray diffraction, have cations exhibiting Rh–H–C \(\sigma\)-interactions which are modulated by both the chelating ligand and the identity of the alkane, while all sit in an octahedral anion microenvironment. These range from chelating \(\eta^2\eta^2\) Rh–H–C (e.g., \([\text{Rh}(\text{Cy}_2\text{P}(\text{CH}_2)_2(\text{CH})(\text{CH}_2)_2\text{PCy}_2)(\text{L})]\text{[BArF}_4\text{]} (n = 3 and 4), through to more weakly bound \(\eta^1\) Rh–H–C in which C–H activation of the chelate backbone has also occurred (e.g., \([\text{RhH}(\text{Cy}_2\text{P}(\text{CH}_2)_2(\text{CH})(\text{CH}_2)_2\text{PCy}_2)(\text{L})]\text{[BArF}_4\text{]}), and ultimately systems where the alkane is not ligated with the metal center, but sits encapsulated in the supporting anion microenvironment, \([\text{Rh}(\text{Cy}_2\text{P}(\text{CH}_2)_2\text{PCy}_2)]\text{[COACBArF}_4\text{]}\), in which the metal center instead forms two intramolecular agostic \(\eta^1\) Rh–H–C interactions with the phospine cyclohexyl groups. \(\text{CH}_2\text{Cl}_2\) adducts formed by displacement of the \(\eta^1\)-alkanes in solution (n = 5; L = NBA, COA), \([\text{RhH}(\text{Cy}_2\text{P}(\text{CH}_2)_2(\text{CH})(\text{CH}_2)_2\text{PCy}_2)(\text{L})\text{[BArF}_4\text{]}\), are characterized crystallographically. Analyses via periodic DFT, QTAIM, NBO, and NCI calculations, alongside variable temperature solid-state NMR spectroscopy, provide snapshots marking the onset of \(\eta\)-alkane interactions along a C–H activation trajectory. These are negligible in \([\text{Rh}(\text{Cy}_2\text{P}(\text{CH}_2)_2\text{PCy}_2)]\text{[COACBArF}_4\text{]}\), in \([\text{RhH}(\text{Cy}_2\text{P}(\text{CH}_2)_2(\text{CH})(\text{CH}_2)_2\text{PCy}_2)]\text{[BArF}_4\text{]}\), \(\sigma\text{C–H} \rightarrow \text{Rh}\sigma\text{-donation is supported by} \text{Rh} \rightarrow \sigma^\text{C–H} \\text{preagostic} \text{donation, and in} \text{[Rh}(\text{Cy}_2\text{P}(\text{CH}_2)_2\text{PCy}_2)(\eta^1\text{COA})]\text{[BArF}_4\text{]}\), \(\sigma\text{C–H} \rightarrow \text{Rh}\sigma\text{-donation dominates, supported by classical} \text{Rh} \rightarrow \sigma^\text{C–H} \pi\text{-back-donation. Dispersive interactions with the} \text{[BArF}_4\text{]}^{-} \\text{anions and Cy substituents further stabilize the alkane within the binding pocket.}

1. INTRODUCTION

The ability to tune the local environment around a metal center by variation of supporting ligands is an important concept widely used in homogeneous organometallic synthesis and catalysis.\textsuperscript{1,2} A well-documented example of this comes from bidentate phosphine ML\textsubscript{2}-type complexes,\textsuperscript{3,4} as by altering the L–M–L bite-angle and substitution at phosphine the resulting steric (e.g., the solid-cone angle, Θ), or electronic (e.g., oxidation state\textsuperscript{5} or degree of bond activation\textsuperscript{6}), changes ultimately can provide the ability to control structure, speciation, and, through the energetics of elementary reaction steps in catalysis, activity and selectivity. Figure 1A.

Extending such concepts to heterogeneous systems is difficult given the resulting challenges associated with precisely defining single-site active centers and their extended coordination environments.\textsuperscript{8} While chelating phosphine complexes supported by metal–organic frameworks,\textsuperscript{9} porous coordination polymers,\textsuperscript{10} nanoparticles,\textsuperscript{11} mesoporous hosts,\textsuperscript{12} and silica surfaces\textsuperscript{13} have...
been reported, the role of the chelating ligand in determining structure and reactivity is less well-developed. Nevertheless, precise control of well-defined, and reactive, metal centers in heterogeneous systems could lead to enhanced activity and selective catalysis, as frequently demonstrated in homogeneous processes.1,4

We have recently shown that single-crystal to single-crystal (SC−SC) solid/gas reactions between H2 and the appropriate [RhL2(diene)]+ precursors form well-defined but reactive σ-alkane complexes directly in the solid-state, e.g., [Rh(Cy2P(CH2)2PCy2)(η3-η2-NBA)][BArF4], [1-NBA][BArF4] (NBA = norbornane, ArF = 3,5-(CF3)2C6H3), Figure 1B).17−20 Such σ-complexes contain 3-center 2-electron (3c2e) Rh−H bonds21,22 and are of general interest from the fundamental challenges presented by their synthesis and characterization,13,27−30 as well as their central role as intermediates in C−H activation processes.23−26 When prepared in this way, these σ-alkane complexes show remarkable relative stability compared with species prepared by solution routes; the latter are generally characterized in situ using NMR spectroscopy, on a small scale (2−20 mg) at very low temperature, and have limited lifetimes even under these relatively constrained conditions.27−31

This stability in the solid-state originates from the [BArF4]− anions providing a robust, octahedral, crystalline microenvironment32 that allows for isolation, characterization, and onward reactivity of the encapsulated organometallic cation to be studied in detail (Figure 1C).26,33 These so-called34 solid-state molecular organometallic (SMOM) systems are related to supported organometallic catalysts (SOMC),13 single-site heterogeneous catalysts (SSHC),35 and MOF-functionalized organometallics9,35−37 but, in contrast to these, are not supported by a platform material. Moreover, SMOM systems have the desirable properties of being readily studied at the molecular-level by single-crystal X-ray diffraction, solid-state NMR (SSNMR) spectroscopy, and computational techniques such as periodic DFT.

We now report that systematic variation of the P−Rh−P bite angle with the identity of the diene in SMOM systems based upon precursors [Rh(Cy2P(CH2)2PCy2)(diene)][BArF4] (n = 3 to 5, diene = norbornadiene, NBD, or 1,5-cyclooctadiene, COD, Scheme 1) results in significant changes in structure and reactivity on addition of H2 in SC−SC reactions. This results in crystallographically characterized σ-alkane complexes that show markedly different degrees of Rh−H−C interaction in response to the changes in both phosphate and the precursor diene, while they are stabilized in the microenvironment provided by the octahedral arrangement of [BArF4]− anions: these range from chelating η3η2 Rh···H−C, through to more weakly bound η1−η1 Rh−H−C and ultimately to systems where the alkane is not ligated with the metal center but sits encapsulated in the anion framework.

2. RESULTS AND DISCUSSION

2.1. Precursor Diene Complexes. Precursor complexes of the general formula [Rh(Cy2P(CH2)nPCy2)(diene)][BArF4] (diene = NBD or COD) were prepared in which the phosphine and diene are systematically varied: n = 3, [2-diene][BArF4]; n = 4, [3-diene][BArF4] n = 5, [4-diene][BArF4] (Scheme 2). These

![Scheme 1. Precursor Diene Complexes Used in This Study and SC−SC SMOM Synthesis of σ-Complexes](image-url)

**Scheme 2. (A) Synthesis of Diene Precursors and (B) Representative P−Rh−P Bite-Angles (β) Taken from Diene Structures**

- **B**[1-diene][BArF4] β = 85.21°
- **B**[2-diene][BArF4] β = 53.91°
- **B**[3-diene][BArF4] β = 96.51°
- **B**[4-diene][BArF4] β = 105.1°

n = total number of CH2 groups.

are conveniently prepared by reaction of [Rh(COD)n][BArF4] with Cy2P(CH2)nPCy2 to give [Rh(Cy2P(CH2)nPCy2)(COD)][BArF4], followed by addition of H2/1,2-F2C6H4/NBD to give [Rh(Cy2P(CH2)nPCy2)(NBD)][BArF4] via isotope formation of difluorobenzene-bound intermediates [Rh(Cy2P(CH2)nPCy2)(1,2-F2C6H4)][BArF4]. Both COD and NBD precursors were isolated in good (~80%) yield after recrystallization from CH2Cl2/pentane. Complexes [1-diene][BArF4] (n = 2) have previously been reported.18

These precursor complexes have been characterized by solution NMR spectroscopy and single-crystal X-ray diffraction, the latter which shows an O6 arrangement of [BArF4]− anions.
surrounding the organometallic cations, as observed for [1-NBA][BArF]_4^{18} and related complexes.17,20 The Supporting Information details their structures. For the NBD precursors, this homologous series allows for the bite-angle (β) of the various diphosphines in this environment to be compared. Unsurprisingly, β becomes progressively larger with an increasing number of methylene units in the chelate backbone (Scheme 2B). The same trend, albeit interestingly with slightly smaller β-angles, is apparent for the COD precursors. In this complex in hand a systematic study of solid/gas hydrogenation was undertaken.

2.2. Hydrogenation of [Rh(Cy_2P(CH_2)3PCy_2)]^+/COD.

As previously reported,14 hydrogenation of [1-NBD][BArF]_4-gives [1-NBA][BArF]_4-in a rapid (less than 10 min) SC–SC transformation (see Figure 1B). Here, use of [1-COD][BArF]_4 results a slower10,41 reaction with H_2 (3 h) and loss of crystallinity. Dissolving the resulting solid in CD_2Cl_2 afforded the previously reported zwitterion [Rh(Cy_2P(CH_2)3PCy_2)(η^5-C_5H_4(CF_3)2)][BArF]_4], [1-BArF]_4, and free COA.18

2.3. (Rh(Cy_2P(CH_2)3PCy_2))^-/NBA: An η^6-η^2-Alkane Complex.

Addition of H_2 (1 bar, 298 K) to single-crystals of [Rh(Cy_2P(CH_2)3PCy_2)(NBD)][BArF]_4, [2-NBD][BArF]_4, resulted in the rapid (~5 min) formation of the σ-alkane complex [Rh(Cy_2P(CH_2)3PCy_2)(η^6-2-NBA)][BArF]_4, [2-NBA][BArF]_4, in an SC–SC transformation, as shown in single-crystal X-ray diffraction (Figure 2) and ^31P{1H}/13C{1H} SSNMR spectroscopies. The octahedral arrangement of [BArF]_4^- anions is retained in [2-NBA][BArF]_4, while the central cation is pseudo square-planar, with the (RhL)_2^- fragment bound to the alkane NBA through two endo Rh···H–C σ interactions showing relatively short Rh···C distances [Rh···C 2.408(2)/2.402(2) Å] and rather acute ∠RhHC, e.g., Rh1−H1A−C1 105.1(2); Rh1−H2A−C2 106.0(2); ∠P1P2Rh/Rh1C1C2 5.15(7).

SSNMR spectroscopies. The octahedral arrangement of [BArF]_4^- anions is retained in [2-NBA][BArF]_4, while the central cation is pseudo square-planar, with the (RhL)_2^- fragment bound to the alkane NBA through two endo Rh···H–C σ interactions showing relatively short Rh···C distances [Rh···C 2.408(2)/2.402(2) Å] and rather acute ∠RhHC, e.g., Rh1−H1A−C1 105.1(2). These H atoms were located and freely refined. These data suggest an η^6-η^2 chelating Rh···H–C motif,42 as corroborated by computational studies (see later). Despite the P–Rh–P bite-angle increasing compared with [1-NBA][BArF]_4 (e.g., Scheme 2B), the Rh···C distances are not different within error [cf. 2.389(3)/2.400(3) Å] and the structures are very similar, suggesting that the NBA ligand fits comfortably into the ligand pocket defined by the Cy groups. This similarity is not strongly influenced by the anion microenvironment as evidenced by calculations on isolated cations (Section 2.7 and Supporting Information). In the solid-state, there are a number of weak C–H···F interactions between the NBA ligand and the [BArF]_4^- anion, Figure S73.

The ^31P{1H} SSNMR spectrum of [2-NBA][BArF]_4 shows two relatively sharp environments at δ = 50.6, 51.6 ([J(RhP) ~170 Hz], while the ^31C{1H} NMR spectrum is featureless between δ 110 and 50, demonstrating hydrogenation of the NBD. A 1^H/13C frequency switched Lee–Goldburg (FSLG) HETCOR experiment at 298 K, which has been used to characterize E–H–M interactions in the solid-state (E = Si, C),18,26,43 shows two strong correlations between δ(^13C) ~26 and δ(^1H) = 2 which are consistent with the crystallographically inequivalent Rh···H–C interactions observed in the solid-state (Figure S13). An additional correlation [δ(^13C) 42/δ(^1H) = −0.6]44 is assigned to the CH_3 bridge on the norbornane, which is affected by [BArF]_4^- ring-current effects as described for [1-NBA][BArF]_4 and related complexes.18,19,26

Dissolving crystalline material of [2-NBA][BArF]_4 in CD_2Cl_2 at 183 K results in free NBA being observed by 1^H NMR spectroscopy and a ^31P{1H} NMR spectrum that is suggestive of a solvent-coordinated complex, [Rh(Cy_2P(CH_2)3PCy_2)- (ClCH_2Cl)][BArF]_4, δ 47.4 ([J(RhP) = 198 Hz], similar to that reported for [Rh(Pz_2P(CH_2)3Pz_2)(ClCH_2ClCl)][BArF]_4]. On warming, decomposition occurs via C–Cl activation to give a mixture of partially soluble chloride-bridged hydride dimers, e.g., [Rh(Cy_2P(CH_2)3PCy_2)H(μ-Cl)][BArF]_4, that precipitate from solution and are best identified by ESI-MS. The formation of the [BArF]_4^-coordinated zwitterion was not observed,45 in contrast to [1-NBA][BArF]_4 that forms [1-BArF]_4 in CD_2Cl_2.18 We suggest this is a consequence of the increased steric profile of the chelating phosphine Cy_2P(CH_2)3PCy_2 versus Cy_2P(CH_2)3PCy_2, disfavoring coordination of the, local to the metal center, planar and bulky [BArF]_4^- anion, coupled with the wider bite-angle phosphines encouraging oxidative addition at Rh(I).6

2.4. (Rh(Cy_2P(CH_2)3PCy_2))^-/COA: A 12-Electron Rh(II) Complex Supported by Agostic Interactions with an Encapsulated Nonbonding Alkane. Exposing single crystals of [2-COD][BArF]_4 to H_2 for 3 h results in, slower,40,41 SC–SC hydrogenation and expulsion of cyclooctane (COA) from the metal center to form formally 12-electron "naked"46,47 [Rh(Cy_2P(CH_2)3PCy_2)]^-/COA, [2^-]. Remarkably, the free alkane is retained inside the anion octahedral cavity to give [Rh(Cy_2P(CH_2)3PCy_2)][COACBArF]_4, [2][COACBArF]_4, Scheme 3.

Scheme 3. Synthesis of [2^-][COACBArF]_4

The solid-state structure of the cation [2^-] (Figure 3A) shows two δ-agostic38–56 Rh···H–C interactions from the cyclohexyl rings [Rh···C 2.91(1) Å, Rh···C 2.87(1) Å] that form in response to the unsaturation now at the Rh(I) metal center. The Rh1−P1−C1 angle reflects this, for example, being more acute [108.9(3)^o] than Rh1−P1−C13 [119.8(3)^o]. The Rh center also moves toward the C–H bonds involved in these agostic interactions, as shown by the angles ∠P1P2C25C27/Rh1P1P2 = 42.6(2)^o (Figure 3B).
The relatively long Rh···C distances, coupled with more open $\angle$RhHC angles, e.g., Rh1···C9 = 2.912(10); Rh1···C19 = 2.873(10); Rh1···P1 = 2.171(2); Rh1···P2 = 2.166(2); P1–Rh1···P2 = 91.21(8); $\angle$P1P2C25C27/Rh1P1P2 = 42.6(2). (B) Displacement of the Rh center in [2]$^+$ toward the agostic C–H bonds in the major disordered component. (C) Ball and stick representation of the two disordered components in [2]$^+$. (D) Packing diagram of [2][COACBAr$_4^-$] showing the O$_3$ arrangement of [BAr$_4^-$] and COA (C = red) shown at van der Waals radii, and only one disordered component shown, Rh1···C28 = 3.74(1) Å.

Figure 4. (A) $^{13}$C($^1$H) SSNMR spectra (10 kHz, 158 K) and NQS spectra of [2][COACBAr$_4^-$] (10 kHz, 158 K). $^*$ = spinning sideband. (B) Proposed fluxional processes ($^\oplus$ = [BAr$_4^-$]).

are consistent with the encapsulated COA undergoing a low-energy site-exchange within the cavity (Figure 4B), suggested to be due to 1,2-jumps and/or exchange between the two disordered COA components. To calibrate our observations, a variable temperature NQS experiment on [1-NBA][BAr$_4^-$] showed an NBA fragment undergoing motion at 298 K which is halted at 158 K, fully consistent with previous variable temperature SSNMR studies (Figure S3). [2][COACBAr$_4^-$] is not stable in solution. Vacuum transfer of CD$_2$Cl$_2$ onto solid [2]-[COACBAr$_4^-$] and warming to 183 K resulted in a precipitate that was persistent on warming to room temperatures. ESI-MS shows this to contain multiple dimeric hydrido-chlorides.

The structural changes evident between [2-NBA][BAr$_4^-$], a $\eta^1$$\eta^2$ $\sigma$-alkane complex, and [2][COACBAr$_4^-$], with a nonbonding alkane, can be traced back to the change in hydrocarbon, as the {ML$_4^+$} fragment is the same. Consideration of the van der Waals surfaces of NBA versus COA, Figure 5, shows that the latter presents a larger steric profile for the metal center. We suggest that this, alongside possible conformational preferences for metal binding of the alkane and noncovalent F···H–C interactions in the microenvironment (see Figures S73 and S76), are drivers for the different structural motifs observed.
2.5. \{Rh(Cy2P(CH2)4PCy2)\}+/NBA: An \(\eta^3,\eta^2\)-Alkane Complex. Addition of \(\text{H}_2\) to single-crystals of \([\text{Rh}(\text{Cy}_2P-(\text{CH}_2)_4P\text{Cy}_2)(\text{NBD})][\text{BArF}_4]\), \([\text{3-NBD}][\text{BArF}_4]\), resulted in a fast (~5 min as measured by \(^{31}\text{P}\{^1\text{H}\}\) SSNMR spectroscopy) SC–SC transformation to give the corresponding \(\sigma\)-alkane complex \([\text{Rh}(\text{Cy}_2P(\text{CH}_2)_4P\text{Cy}_2)(\eta^3\eta^2\text{-NBA})][\text{BArF}_4]\), \([\text{3-NBA}][\text{BArF}_4]\), Figure 6. The solid-state structure of

\[\text{[3-NBA][BArF}_4\] reveals a \(\sigma\)-bound NBA ligand, with two Rh–\(\text{H}\)–C interactions using the \(\text{endo}\) \(\text{C–H}\) bonds (H atoms located). Despite the bite-angle increasing further compared with those of \([1\text{-NBA}][\text{BArF}_4]\) and \([2\text{-NBA}][\text{BArF}_4]\), the key metrics associated with this interaction remain essentially unchanged: Rh1–C1, 2.399(2) \(\AA\); Rh1–C2, 2.396(2) \(\AA\); Rh1–P1, 2.211(4) \(\AA\); Rh1–P2, 2.221(4) \(\AA\); P1–Rh1–P2, 97.87(2)°.

Increasing the bite-angle of the phosphine promoted different reactivity in the resulting \(\sigma\)-alkane complex. Surprisingly given that the structural metrics have not changed significantly from the smaller bite-angle congeners, \([\text{3-NBA}][\text{BArF}_4]\) is not stable when exposed to a moderate vacuum for 3 days. Crystallinity is lost, and SSNMR spectroscopy shows the formation of multiple species, as yet unidentified. Thus, although the binding of the NBA ligand appears to not be influenced significantly by the increase in bite-angle of the chelating phosphine, in the measured ground-state structure steric pressure and/or enhanced stability of any decomposition products as driven by the change in phosphine appear to promote reactivity toward loss of NBA. Hydrogenation of single-crystals of \([\text{3-COD}][\text{BArF}_4]\) in a solid/gas reaction resulted in loss of crystallinity. We have not characterized the product of this further.

2.6. \{Rh(Cy2P(\text{CH}_2)_4P\text{Cy}_2)\}+/COA and NBA: Phosphine Ligand Backbone \(\text{C–H}\) Activation, Structural Reorganization with Retention of Crystallinity, and Rh(III) \(\eta^1\)-\(\sigma\)-Alkane Complexes. Addition of \(\text{H}_2\) to crystalline \([\text{4-NBD}][\text{BArF}_4]\) resulted in a rapid (~5 min as measured by \(^{31}\text{P}\{^1\text{H}\}\) SSNMR spectroscopy) SC–SC reaction. Analysis of the product formed using single-crystal X-ray diffraction was hampered by long-range disorder, which is also present in the starting material. The structure was modeled using a supercell \((Z' = 2)\) which gave a satisfactory solution \((R = 15.7\%)\) that allowed for the gross structure of the cation to be determined, Figure 7, but does not allow for detailed metrics to be discussed.

Hydrogen atoms were not located, and the NBA fragments formed by hydrogenation were necessarily modeled as rigid bodies. There are two chemically very similar, but crystallographically independent cations in this supercell in which each has a disordered NBA over two conformations (Figure 7C). There is no crystallographically imposed local symmetry. The \(\sigma\)-NBA arrangement of anions in relation to each cation is retained (Figures S83–S86).

Despite the challenges associated with structural identification, it is immediately apparent that the phosphine pentamethylene backbone has undergone a \(\text{C–H}\) activation in the solid-state to form a wide bite-angle \(\text{trans}\)-spanning phosphine PCP pincer complex. Such intramolecular \(\text{C–H}\) activation with an \(\eta^2\)P(\(\text{CH}_2\))\(_2\)PR\(_2\) ligand has precedent in solution studies, either to form a hydrido-alkyl complex\(^{68,69}\) or through a further \(\alpha\)-elimination to give a diphosphino-carbene complex.\(^{69}\) Solution trapping experiments \((\text{vide infra})\) show that the former has occurred in \([\text{4-NBA}][\text{BArF}_4]\), and thus, a formulation of \([\text{Rh}(\text{Cy}_2P(\text{CH}_2)_2(\text{CH})(\text{CH}_2)_2P\text{Cy}_2)\text{H}(\eta^1\text{-NBA})][\text{BArF}_4]\), \([\text{4-NBA}][\text{BArF}_4]\) is proposed. The disordered NBA ligand shows a range of Rh–C distances to the Rh(III) center [2.75–3.10 \(\AA\)] and interacts via either the basal or bridge methylene groups.

Figure 5. van der Waals\(^{65}\) surfaces for NBA and COA.

Figure 6. (A) SMOM synthesis of \([3\text{-NBA}][\text{BArF}_4]\). (B) Cation of \([3\text{-NBA}][\text{BArF}_4]\) (50% displacement ellipsoids): Rh1–C1, 2.399(2) \(\AA\); Rh1–C2, 2.396(2) \(\AA\); Rh1–P1, 2.211(4) \(\AA\); Rh1–P2, 2.221(4) \(\AA\); P1–Rh1–P2, 97.87(2)°.

Figure 7. (A) Synthesis of \([4\text{-NBA}][\text{BArF}_4]\). (B) Ball and stick representation of one of the crystallographically independent cations in the solid-state showing one disordered NBA component, Rh–C10, \(\sim 2.04\ \AA\); P–Rh–P, \(\sim 167°\). (C) Representation of the four disordered NBA fragments at the two crystallographically independent cations with Rh–C(alkane) distances. Hydride positions were not determined, Cy groups not shown.
These distances reflect weak (at best) σ-interactions compared to, e.g., [2-NBA][BARF]₄,₄⁹ while this spread suggests that the NBA fragment finds a better spatial fit with the {RhPCP}° fragment for some conformations of the data. Overall, do not allow the precise binding mode of the alkane (η²-HC, η²-H₂C⁷⁰) to be determined. A related SC–SC N–C oxidative addition at a Rh(1) center has been reported in Rh–PNP pincer complexes.₇¹ [4-NBA][BARF]₄ is stable indefinitely in an Ar-filled glovebox or under vacuum.

The 298 K ¹³C{¹H} SSNMR spectrum of [4-NBA][BARF]₄ shows a featureless region between δ 116 and 59, demonstrating hydrogenation of the diene. The 298 K ¹³C{¹H} SSNMR shows a tightly coupled ABX system,⁷² which is less well-resolved at 158 K, consistent with inequivalent trans-phosphines that are in chemically very similar environments bound to a Rh(III) center: δ 64.1, 63.4 [J(RhP) = 605, J(PP) = 325 Hz] (Figures S49 and S50). The ¹³C NQS spectrum at 158 K shows at least four signals grouped between δ 38–35 and δ 29–27, in the region associated with aliphatic C–H groups, which indicate a low-energy molecular motion of the NBA ligand within the cavity of the cage (Figure S54). Such a low-energy process is consistent with the disorder of the NBA fragment modeled in the solid-state. In the 158 K FSLG HETCOR spectrum, cross peaks between these aliphatic signals in the ¹³C SSNMR spectrum and low-field peaks in the ¹¹H projection (δ −1.8 to −2.6) are observed. We assign these to the H–H–C interactions, although we cannot discount ring-current effects from the proximal A₃ groups causing such a high-field shift in other C–H bonds.¹⁸,²⁶

Unlike for [2-NBA][BARF]₄ or [3-NBA][BARF]₄, dissolving [4-NBA][BARF]₄ in CD₂Cl₂ gave a stable complex that could be characterized by solution NMR spectroscopy and single-crystal X-ray diffraction (crystals grown from CH₂Cl₂/pentane) as [Rh(Cy₂P(CH₂)₂(CH)(CH₂)₂PCy₂)H(CO)][BARF]₄, [4-CH₂Cl₂][BARF]₄, Figure S8, in which the NBA ligand has been replaced by a CH₂Cl₂ ligand. Vacuum transfer of the volatiles demonstrates NBA is liberated, consistent with the initial solid/gas hydrogenation of the NBD to form [4-NBA][BARF]₄. The molecular structure of [4-CH₂Cl₂][BARF]₄, Figure S8B, does not suffer from disorder and clearly shows the trans-spanning PCP pincer motif suggested for [4-NBA][BARF]₄. The Rh–H hydride (H1) was located, sitting trans to a vacant site, and anti to the remaining hydrogen associated with the C–H activated methylene group (H3). This stereochemistry is as expected for an intramolecular C–H activation.₆₆,₆₈ A CH₃Cl molecule has displaced the labile NBA fragment. Displacement of a weakly bound σ-alkane ligand by halogenated solvent is well-established,₆₈,₇₈,₃⁰ and the structure is consistent with other crystallographically characterized Rh–CICl₃Cl complexes.₄⁹,₇₅,₇₆ [4-CH₂Cl₂][BARF]₄ is a 16-electron Rh(III) complex, but there is no evidence for any significant supporting agostic interaction from the cyclohexyl groups: closest Rh–C = 3.261(3) Å. Although this is not an SC–SC transformation, the O₅ arrangement of anions is retained in the extended solid-state structure of recrystallized material.

Solution NMR data for [4-CH₂Cl₂][BARF]₄ at 298 K (CD₂Cl₂) reveal that a fluxional process is occurring. In the ¹¹H NMR spectrum relatively broad signals are observed for the phosphine ligand, and no characteristic signal due to the C–H activated methylene (ca. 3 ppm) or Rh–H was observed. The ³¹P{¹H} NMR spectrum showed a relatively sharp doublet at δ 66 [(J(RhP) = 121 Hz). Cooling to 243 K results in a sharpening of the aliphatic region in the ¹¹H NMR spectrum, and two new signals at δ 2.71 and −27.2 [δ (J(RhH) = 55 Hz, br, fwhm ~40 Hz) appear which integrate to 1 H each. These are assigned to the C–H activated methylene (i.e., C3) and Rh–H, respectively, the latter with a chemical shift that places it trans to a vacant site.₆₅,₇₅,₇₆ A spin-saturation experiment at this temperature shows that these two signals are undergoing slow mutual exchange. The ³¹P{¹H} NMR spectrum is still a doublet but is shifted slightly to lower field [δ 64.4]. These low-temperature data are fully consistent with the solid-state structure of [4-CH₂Cl₂][BARF]₄. An exchange process that involves reversible reductive C–H bond forming/C–H oxidative addition is proposed, as suggested for closely related systems,₆₆ and DFT calculations confirm this is favored (ΔG°calc = 18.7 kcal/mol) over an alternative α–elimination process via a diphosphino–carbene intermediate (ΔG°calc = 27.4 kcal/mol, see Figure S105, Supporting Information).₆₅ It is also likely that the bound CH₂Cl₂ molecule is undergoing rapid exchange at the metal center with the solvent.

If [4-COD][BARF]₄ is subjected to H₂ in the solid-state, after 30 min crystallinity is lost. However, if the reaction is stopped after only 10 min and the resulting single crystals are quickly transferred to an X-ray diffractometer and cooled to 150 K, the resulting analysis shows that a new complex is formed in 30% yield in a SC–SC process, with the remaining being unreacted [4-COD][BARF]₄. These data showed this new complex to be [4-COA][BARF]₄, [Rh(Cy₂P(CH₂)₂(CH)(CH₂)₂PCy₂)H(η¹-COD)][BARF]₄. Although the single-crystal refinement showed a superposition of mixture of [4-COD][BARF]₄ (70%) and [4-COA][BARF]₄ (30%) in the O₅-anionic cage, refinement of the constituent components gave a reliable and robust solution (R = 9.6%).

The molecular cation of [4-COA]⁺ is shown in Figure 9. This shows a C–H activated, trans-spanning, diphosphine “PCP” pincer ligand with a cyclooctane located in close proximity to the Rh(III) metal center [Rh1···C1a, 2.90(3) Å]. The COA ligand is not disordered and shows that all the C–C bonds are single [1.46(2)–1.48(2) Å]. The Rh···C distance is very long compared with other Rh···H–C σ-alkane complexes, [1-pentane]-[BARF]₄, 2.522(5) Å, in which the pentane acts as a bidentate ligand.₇₆ However, it is considerably shorter than found in [2][COACBArF]₄ (where we propose a minimal interaction at best) and is of a similar distance to the weak agostic interaction in trans-[Rh(2,2'-biphenyl)(P(Bu)₃)][BARF]₄ 2.979(4) Å, as
also interrogated by QTAIM analysis. This distance, combined with a rather open Rh1a-C5H5(Alkane) interaction. The hydrogen atoms were not located, disordered in a calculated position of 140.7(2)°C and decomposition products. The sensitivity of the di-alkane complex bound to Rh(III) species (see Supporting Information for details and tables 1-4). The increased polarity of the E−H bond in these analogues will make a significant contribution to bonding, and thus, they are sufficiently stable to observe using solution NMR techniques, unlike [4-COA][BArF4].

If hydrogenation of [4-COD][BArF4] is continued for a total of 30 min, decomposition to an, as yet unidentified, product(s) is observed upon dissolution in CD2Cl2, from which a featureless 31P{1H} NMR spectrum and a very broad 1H NMR spectrum are observed. We speculate that this signals the formation of a paramagnetic Rh(II) dimeric complex on dissolution, but the identity of this species remains to be resolved. Attempts to obtain meaningful SSNMR data for [4-COA][BArF4] were hampered by temporal and temperature sensitivity that was amplified by the requirement to use finely crushed material for analysis by SSNMR that meant that crystallinity is lost much faster than for larger samples. In the 31P{1H} SSNMR spectrum at 158 K, a major, broad peak at δ 64 is observed (being similar to that seen for [4-NBA][BArF4]), alongside [4-COD][BArF4] and decomposition products. The sensitivity of [4-COA]-[BArF4] contrasts with the relative stability of [4-NBA][BArF4] or [2][COACBArF4] and perhaps reflects the combination of the different steric profile of the alkane in the former (NBA versus COA) combined with the stabilizing influence of agostic interactions in the latter.

[4-NBA][BArF4] and [4-COA][BArF4] are shown to have very similar structures, with the former’s stability allowing for a more detailed characterization by SSNMR spectroscopy and the latter providing a good structural solution by X-ray crystallography. Combined, they thus provide a convincing analysis as a weakly bound σ-alkane complex bound η1 at a Rh(III) center. We believe they are the first Rh(III) σ-alkane complexes isolated, or observed, by any method.

2.7. Computational Studies. Periodic DFT calculations were performed on the extended solid-state structures of [X-NBA][BArF4] (X = 1, 2, and 3), [2][COACBArF4], and [4-COD][BArF4] to assess the structure and bonding of these species (see Supporting Information for details and tables of computed structures). For the [X-NBA][BArF4] series geometries optimized with the PBE-D3 approach provided good agreement with the experimental structures. For [2][COACBArF4] both the major and minor components were computed and structural metrics around the Rh centers were again well-reproduced. However, more movement of the COA was seen in these calculations, perhaps reflecting the absence of significant bonded interactions between Rh and the COA (see below). For [4-COA][BArF4] the calculations slightly underestimate the Rh1⋯C1 distance (ca 2.80 Å; exp 2.90(3) Å).
Given the variations between computed and experimental structures across the range of systems under consideration, the subsequent analyses were based on computed structures in which the Rh, C, B, and P positions were taken from the crystallographic studies and the H and F atoms were optimized with the PBE-D3 approach. Selected distances involving key H atom positions optimized on this basis are shown in Figure 10.

Figure 10. Computed distances (Å) involving key H atoms in [X-NBA]-[BAR\textsubscript{4}]\textsuperscript{2-} (X = 1, 2, and 3; \(n = 0, 1, \) and 2, respectively), [2][COAc-BAR\textsubscript{4}]\textsuperscript{4-}, and [4-COD][BAR\textsubscript{4}]\textsuperscript{4-}. ‘data are for endo-C–H bonds: all exo-C–H bond distances fall between 1.094 and 1.100 Å. a structure based on optimization of the major component.

A more quantitative analysis of bonding was then provided by quantum theory of atoms in molecules (QTAIM) and natural bond orbital (NBO) second order perturbation donor–acceptor interaction analyses performed on the isolated cations shown in Figure 10, while noncovalent interaction (NCI) plots were run on ion pairs featuring the nearest-neighbor [BAR\textsubscript{4}]\textsuperscript{4-} anion.

2.7.1. [X-NBA][BAR\textsubscript{4}]\textsuperscript{4-} (X = 1, 2, and 3). Computed structures for all three species show short Rh···H11/H21 contacts of around 1.88 Å and elongation of the C1–H11/C2–H21 bonds to ca. 1.15 Å consistent with the presence of two 3c–2e C–H···Rh σ-interactions in each case. QTAIM and NBO analyses on the [2-NBA]\textsuperscript{4-} cation confirm this (Figure 11A–C), with the presence of Rh···H11 and Rh···H21 bond paths and reduced bond critical point (BCP) metrics for C1–H11 and C2–H21 compared to the spectator C1–H21/C2–H22 bonds. NBO calculations highlight the dominance of C–H → Rh σ-donation into the trans-\(\sigma_{\text{Rh–H}}\) orbital, reinforced by \(\pi\)-back-donation from a Rh lone pair (d orbital) and the cis-\(\sigma_{\text{Rh–C}}\) bonding orbital. Similar results were computed for [1-NBA]\textsuperscript{4-} and [3-NBA]\textsuperscript{4-} (see Supporting Information) indicating that changing the bite-angle has a minimal effect on the Rh···H interaction.

Figure 11D shows the NCI plot of the [2-NBA][BAR\textsubscript{4}]\textsuperscript{4-} ion pair and reveals a broad curved feature running roughly parallel to the H11–C1–C2–H21 bonds. This reflects the chelating nature of the NBA ligand and is predominantly stabilizing (blue) in character, while also exhibiting a central destabilizing (orange/red) region that is consistent with the presence of the ring critical point (RCP) in the QTAIM study. Some destabilizing character is also seen between Rh and the center of the two C–H bonds (see detail in Figure 11E). This suggests two cyclic [RhCH] features in the electron density topology that are consistent with an \(\eta^1\)-interaction and the significant contribution of classical Rh–H(dz\textsuperscript{2}) to \(\sigma^*_{\text{C–H}}\) \(\pi\)-back-donation identified in the NBO analysis. This also highlights how the NCI approach can amplify the insight gained from the local QTAIM critical points.\textsuperscript{87–89} These features contrast with the more localized \(\eta^1\)-interactions associated with C–H···Rh bonding in [2][COAc-BAR\textsubscript{4}]\textsuperscript{4-} and [4-COA][BAR\textsubscript{4}]\textsuperscript{4-} (see below). The NCI plot also highlights broad swathes of green that indicate weak, dispersive stabilization between the NBA ligand and (i) the aryl groups of the borate anions and (ii) the cyclohexyl substituents of the cation. Thus, intermolecular dispersion interactions play a crucial role in stabilizing these alkane ligands within the “pocket”.\textsuperscript{90} Similar NCI plots were obtained for [1-NBA][BAR\textsubscript{4}]\textsuperscript{4-} and [3-NBA][BAR\textsubscript{4}]\textsuperscript{4-}, and a side-by-side comparison is provided in Figure S100 in the Supporting Information.

2.7.2. [2][COAc-BAR\textsubscript{4}]\textsuperscript{4-}. QTAIM and NBO data for the [2\textsuperscript{+}] cation are displayed in Figure 12A–C. Rh···H3B and Rh···H9A bond paths signal the presence of intramolecular agostic interactions. The associated Rh···H contacts are longer (ca. 1.94 Å), and the corresponding C–H distances shorter (ca. 1.14 Å), than in the [X-NBA]\textsuperscript{4-} series, suggesting weaker interactions in [2\textsuperscript{+}]. This is confirmed by reduced \(\rho(r)\) values at the Rh–H BCPs and lower \(\sigma_{\text{C–H}}\) trans-\(\sigma_{\text{Rh–H}}\) σ-donation via NBO. NBO, however, also suggests a similar degree of back-donation as [2-NBA]\textsuperscript{4-}, although this is not classical Rh–H(dz\textsuperscript{2}) to \(\sigma^*_{\text{C–H}}\) π-back-donation but rather involves contributions from both the cis- and trans-\(\sigma_{\text{Rh–C}}\) bonds (see also the discussion of [4-COA]\textsuperscript{4-} below). This suggests an \(\eta^1\)-C–H → Rh interaction and is supported by the NCI plot which highlights these stabilizing agostic interactions with well-defined, localized blue disks (Figure 12D,E).

The closest Rh···COA contact in [2][COAc-BAR\textsubscript{4}]\textsuperscript{4-} is via H21 with a computed distance of 2.844 Å. This is well within the sum of the van der Waals radii of Rh and H (3.64 Å),\textsuperscript{65} and a weak BCP is computed between these centers (\(\rho(r) = 0.011\) e Å\textsuperscript{-3} ).\textsuperscript{91} No equivalent donor–acceptor interaction is computed with NBO, although the NCI plot does suggest a weak, stabilizing feature between Rh and H21 (see Figure 12D,E). This is part of a broad area of weakly stabilizing interactions between the COA and the [2\textsuperscript{+}] cation, suggesting that any direct covalent Rh···H21 interaction is at best very weak, if it exists at all. The COA is further stabilized within the cavity by dispersive interactions with the two proximate aryl substituents of the [BAR\textsubscript{4}]\textsuperscript{4-} anion.\textsuperscript{92}
The computed structure of [4-COA]−BArF4 shows a Rh−H11 distance of 2.002 Å and an elongated C1−H11 distance of 1.13 Å (Figure 10). These, along with the computed Rh···H11 BCP metrics (Figure 13), suggest a somewhat weaker σ-interaction than in the [2]+ cation, although NBO indicates a similar degree of σ-donation and, if anything, greater back-donation in this case. A blue/green disk in the NCI plot confirms this η1 C1−H11 → Rh σ-interaction as well as highlights broad areas of stabilizing dispersion interactions with the cyclohexyl substituents and the [BArF4]− aryl groups.

An interesting aspect of the NBO analysis of both agostic [2]+ and [4-COA]− is the degree of donation into σ*C−H from the trans-σRh−L bonding orbitals (L = P2 or C32, respectively). In [4-COA]−, this is supported by donation from the cis-σRh−H2 bonding orbital (see Figure 14). These interactions reflect the η1-orientation of the C−H bonds in these species ([2]+, ζRhHCcalc(ave) = 138°; [4-COA]−, ζRhHCcalc = 133°). Similar σ-donation has been identified with the onset of the C−H−Rh (“pregostic”) interaction93,94 and is consistent with the end-on approach of CH4 in Bürgi–Dunitz trajectories95 and of H2 in oxidative addition reactions.96,97

3. CONCLUSIONS

The studies reported herein provide a demonstration of the power of solid-state molecular organometallic chemistry (SMOM-Chem), and in particular single-crystal to single-crystal transformations to provide access to and, when combined with periodic DFT calculations, characterize a wide range of different σ-alkane M⋯H−C coordination motifs by systematic variation of the ligand set. Figure 15 highlights these, alongside selected structural and computationally determined bonding parameters for the corresponding Rh⋯alkane interactions.
described present snapshots along a continuum of M···H−C interactions that would be very difficult to probe in σ-alkane complexes using solution techniques due to the instability of such systems combined with flexibility between different M···H−C bonds that often results in time-averaged structures in solution, even at very low temperatures. Thus, with the NBA alkane ligand and simple, chelating phosphines, relatively strong bidentate chelating η²-η² motifs are observed, e.g., [2-NBA]-[BARF]. With a trans-spanning C−H activated PCP pincer ligand, reduced access to the metal center results in unprecedented η¹ Rh(III)···H−C motifs being observed in the solid-state, e.g., [4-COA]-[BARF], a model for the early stages of C−H activation at metal centers. Finally, when the steric requirement of the phosphine and the alkane combine with the ability for the phosphine to engage in stabilizing intramolecular agostic interactions, the alkane is expelled from the metal center but remarkably stays encapsulated within the anion framework, providing baseline experimental structural data for a close, but essentially nonbonding, approach of an alkane with a metal center: viz. [2][COACBARF]. Underpinning these remarkable structures is the stabilizing effect of the anion microenvironment, and in particular the role that intermolecular dispersion interactions play in stabilizing these alkane ligands within the binding pocket. Reflecting this, none of the complexes reported are stable in solution even at low temperature. The SMOM technique thus complements elegant low-temperature in situ solution techniques for the synthesis and characterization of σ-alkane complexes.

That such wide variations of alkane binding modes and structures are observed while a well-defined molecular environment is maintained in the solid-state provides an exemplar of a potentially tunable, molecular heterogeneous system that can be precisely characterized. By using a core metal–ligand fragment, i.e., {Rh(diphosphine)}+, it also offers a wide range of potential opportunities for transformations where variation of metal–ligand interactions is likely to influence rate, stability, and selectivity in catalysis. It will be interesting to see if this can be translated to productive C−H activation reactions of hydrocarbons using SMOM systems, and our efforts are currently focused in this direction.

ASSOCIATED CONTENT

Supporting Information
The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/jacs.8b09364.

Synthesis, structural characterization, solution and solid-state NMR experiments, and computational studies (PDF)

Crystallographic data (CIF)

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Notes

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(39) See Supporting Information.


(44) In the 298 K $^{1}H/^{31}C$ HETCOR, additional cross peaks are seen for signals of $\delta^{(1)}H$ 0 and –1 and $\delta^{(13)}C$ 17 and 20. Close inspection of the secondary interactions in [3-NBA]$\text{[BARF}_{4}]_{2}$ reveals a number of C–H bonds in the phosphate that lie over the centers of anion aryl rings (H...C6 centroid 2.82–2.94 Å) and are thus likely to experience ring-current effects. In addition, the NMR fragment is likely undergoing a C2 rotation in the solid-state on the NMR time scale at 298 K, as reported for [1-NBA]$\text{[BARF}_{4}]_{2}$.


(51) NCI plots on [2]$^{+}$ suggest significant intramolecular dispersion stabilization between the Cy groups not involved in the agostic interactions.


(86) A previous study on [1-NBA][Bar4] was used a slightly different protocol (ref 18), and so, this system was recomputed with the current approach for consistency. Data that are very similar to those of our previous study were obtained.


(90) Additional weak Rh–H−−H interactions with similar BCPs metrics were also computed involving cyclohexyl C–H bonds in [3-NBA]1+ and [2]+. See Supporting Information.
The COA sits within a square-pyramidal array of $\text{BARF}_4^-$ anions (cf. Figure 3), and Figure 13 shows the “axial” $[\text{BARF}_4^-]$ anion. Stabilizing noncovalent interactions are also seen for the four basal $[\text{BARF}_4^-]$ anions, but these are less significant (see Figure S91, Supporting Materials).


Similar $\sigma$-donation is also seen in $[2\text{-NBA}]^+$, but this is weak (1.1 kcal/mol, from $cis$-$\sigma_{\text{BAP}}$) reflecting the tighter computed RhHC angle ($102^\circ$).