Single-Crystal to Single-Crystal Addition of H₂ to [Ir(iPr-PONOP)(propene)][BAr₄F] and Comparison Between Solid-State and Solution Reactivity

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ABSTRACT: The reactivity of the Ir(I) PONOP pincer complex [Ir(iPr-PONOP)(η²-propene)][BAr₄F], 6, [Pr-PONOP = 2,6-(Pr₂PO)₂C₆H₄NAr = 3,5-(CF₃)₂C₆H₃] was studied in solution and the solid state, both experimentally, using molecular density functional theory (DFT) and periodic-DFT computational methods, as well as in situ single-crystal to single-crystal (SC-SC) techniques. Complex 6 is synthesized in solution from sequential addition of H₂ and propene, and then the application of vacuum, to [Ir(iPr-PONOP)(η₂-COD)][BAr₄F], 1, a reaction manifold that proceeds via the Ir(III) dihydrogen/dihydride complex [Ir(iPr-PONOP)(H₂)H₂][BAr₄F], 2, and the Ir(III) dihydride propene complex [Ir(iPr-PONOP)(η²-propene)H₂][BAr₄F], 7, respectively. In solution (CDCl₃) 6 undergoes rapid reaction with H₂ to form dihydride 7 and then a slow (3 d) onward reaction to give dihydrogen/dihydride 2 and propane. DFT calculations on the molecular cation in solution support this slow, but productive, reaction, with a calculated barrier to rate-limiting propene migratory insertion of 24.8 kcal/mol. In the solid state single-crystals of 6 also form complex 7 on addition of H₂ in an SC-SC reaction, but unlike solution the onward reaction (i.e., insertion) does not occur, as confirmed by labeling studies using D₂. The solid-state structure of 7 reveals that, on addition of H₂ to 6, the PONOP ligand moves by 90° within a cavity of [BAr₄F]⁻ anions rather than the alkene moving. Periodic DFT calculations support the higher barrier to insertion in the solid state (ΔG° = 26.0 kcal/mol), demonstrating that the single-crystal environment gates onward reactivity compared to solution. H₂ addition to 6 to form 7 is reversible in both solution and the solid state, but in the latter crystallinity is lost. A rare example of a sigma amine-borane pincer complex, [Ir(iPr-PONOP)H₂(η²-H₂B-NMe₅)][BAr₄F], 5, is also reported as part of these studies.

1. INTRODUCTION

The addition of dihydrogen and an alkene to metal centers, followed by migratory insertion and reductive elimination of an alkane, are elementary transformations in organometallic synthesis and catalysis. As well as being the key steps in catalytic alkene hydrogenation, the microscopic reverse of hydrogenation, alkane dehydrogenation, allows for the generation of simple alkenes from their corresponding alkanes, by C–H oxidative addition and β-elimination, Scheme 1A. Iridium complexes based upon the Ir(pincer)H₂ motif (pincer = R-PCP, R-POCOP, or R-PONOP, R = alkyl or aryl, Scheme 1B) are often the systems of choice for alkane dehydrogenation reactions, operating by key, but yet to be experimentally observed, highly reactive Ir(pincer) intermediates such as 14-electron (a) or alkane σ-complexes (e). Under transfer dehydrogenation conditions intermediate a is generated from dihydride b using a sacrificial alkene in a complementary hydrogenation cycle.

We have an interest in the generation and reactivity of σ-alkane complexes (i.e., e) using single-crystal to single-crystal (SC-SC) solid-state molecular organometallic chemistry techniques (SMOM). For example, addition of H₂ to crystalline [Rh(chelating-phosphine)(alkene)][BAr₄F] precursors [ArF = 3,5-(CF₃)₂C₆H₃] results in the formation of the corresponding cationic alkane σ-complexes in a solid/gas SC-SC transformation by hydrogenation of the alkene to form an alkane, which remains bound to the metal center. In solution σ-alkane complexes are transient (lifetimes of μs to hrs), being observed using in situ spectroscopic methods, often at low temperatures. The stability of the σ-alkane complexes in the solid state comes from the [BAr₄F]⁻ anions that provide a microenvironment of secondary noncovalent interactions organized in a tertiary periodic anionic motif. This stability also allows these well-defined σ-alkane complexes to act as catalysts.
to be directly connected with the products of C–H activation, for example, in stoichiometric acceptorless alkane dehydrogenation at room temperature.\textsuperscript{14,15}

We recently showed that this synthetic methodology can be extended to allow for the isolation of a cobalt σ-alkane complex.\textsuperscript{19} In contrast, the iridium analogue cannot be isolated, and a hydride-bridged dimer results.\textsuperscript{20} Inspired by the work of Brookhart and co-workers in exploring the solid/gas SC-SC reactivity of aryl-fluorinated (Aρ\textsuperscript{F}) pincer Ir(Aρ\textsuperscript{F}-POCOP)\textsubscript{H}\textsubscript{2} complexes with alkenes and hydrogen in which hydride-bridging dimers do not form,\textsuperscript{21} and their reports of [M('Bu-PONOP)(CH\textsubscript{2})][BAr\textsubscript{4}\textsuperscript{F}]\textsubscript{2} complexes that are σ-alkane complexes (M = Rh\textsuperscript{18}), or alkyl hydrides (M = Ir\textsuperscript{19}), respectively, in solution at low temperature, we were interested in the SC-SC reactivity of cationic [Ir(PONOP)(propene)]-\textsuperscript{[BAr\textsubscript{4}\textsuperscript{F}]\textsubscript{2}} complexes with H\textsubscript{2} to explore if a propane\textsuperscript{15} (or propyl hydride) complex was accessible. A further motivation for this was the study of the elementary steps and intermediates of alkene hydrogenation/alkane dehydrogenation using Ir-pincer complexes by SC-SC reactivity. Propane to propene dehydrogenation is particularly interesting, as it is industrially relevant,\textsuperscript{14} and solid-phase supported Ir-pincer catalysts have used propene as a sacrificial acceptor in the gas-phase dehydrogenation of light alkanes\textsuperscript{25} as well as catalyzing direct propene dehydrogenation.\textsuperscript{26}

In this contribution we report the synthesis of the new complex [Ir('Pr-PONOP)(propene)][BAr\textsubscript{4}\textsuperscript{F}] and compare its reactivity with H\textsubscript{2} in solution and the solid state, Scheme 2. While this Ir(I) complex reversibly adds H\textsubscript{2} in a solid-state SC-SC reaction that results in significant and unexpected reorientation of the ligand framework, onward reaction to form propane does not occur. By comparison, in solution the formation of the Ir(III) dihydrogen/dihydride complex [Ir('Pr-PONOP)(H\textsubscript{2})][BAr\textsubscript{4}\textsuperscript{F}] results alongside the formation of propane, but with more mechanistic complexity than in the solid state. While, ultimately, a σ-propane complex was not accessible in the solid state, these observations reveal the role of the solid-state environment in mechanically gating organometallic reactivity. A rare example of a σ-bound amine-borane pincer complex is also reported as part of this study.

2. RESULTS AND DISCUSSION

2.1. Solution Synthesis of [Ir('Pr-PONOP)(H\textsubscript{2})][BAr\textsubscript{4}\textsuperscript{F}]\textsubscript{2}, [Ir('Pr-PONOP)(H\textsubscript{2})][BAr\textsubscript{4}\textsuperscript{F}][BAr\textsubscript{4}\textsuperscript{F}][BAr\textsubscript{4}\textsuperscript{F}][BAr\textsubscript{4}\textsuperscript{F}]\textsubscript{2} and [Ir('Pr-PONOP)-H\textsubscript{2}(η\textsuperscript{5}-H\textsubscript{2}B-NMe\textsubscript{2})][BAr\textsubscript{4}\textsuperscript{F}]. A suitable entry point into the synthesis of the desired Ir(I) propene complex is an [Ir((PONOP)(H\textsubscript{2})\textsuperscript{+}) precursor, in the anticipation that reaction with excess propene would generate an Ir(I) propene-bound complex alongside free propane from hydrogenation.\textsuperscript{27,28} The precursor to this, [Ir('Pr-PONOP)(η\textsuperscript{5}-COD)][BAr\textsubscript{4}\textsuperscript{F}], I, was synthesized from addition of free ligand, 'Pr-PONOP, to [Ir(COD)\textsubscript{2}][BAr\textsubscript{4}\textsuperscript{F}] (COD = cyclooctadiene, see the Supporting Information). In the 1\textsuperscript{H} NMR spectrum of complex 1 signals due to bound [δ 4.45] and unbound [δ 5.68] alkene are observed, showing the COD does not reversibly dissociate or undergo intramolecular exchange on the NMR time scale. Resonances assigned to the 'Pr-PONOP ligand indicate overall C\textsubscript{2}v symmetry for the cation, and consistent with this in the 31\textsuperscript{P}{\textsuperscript{1}H} NMR spectrum a single environment is observed.\textsuperscript{30} A simple rotation of the COD ligand would account for these data, as also suggested to occur for the Rh analogue [Rh('Pr-PONOP)(η\textsuperscript{5}-COD)][BAr\textsubscript{4}\textsuperscript{F}].\textsuperscript{31} Addition of excess H\textsubscript{2} (4 bar) to complex 1 in CD\textsubscript{2}Cl\textsubscript{2} solution resulted in the rapid formation (5 min) of the dihydrogen/dihydride complex [Ir('Pr-PONOP)(H\textsubscript{2})][BAr\textsubscript{4}\textsuperscript{F}], 2 (85%), alongside free COD and a complex identified as [Ir('Pr-PONOP)(H\textsubscript{2})(η\textsuperscript{5}-COE)][BAr\textsubscript{4}\textsuperscript{F}], 3 (15%), Scheme 3, (COE = cyclooctene). No free COE was observed. Complex 3 was characterized in the 1\textsuperscript{H} NMR spectrum by the observation of two bound alkene [δ 3.00 and 2.93] and two inequivalent hydride environments [δ -10.41 and -17.77], while an AB doublet is observed in the 31\textsuperscript{P}{\textsuperscript{1}H} NMR spectrum that shows trans JJ'P coupling [280 Hz]. Given that COD does not dissociate rapidly in complex 1, these observations are best explained by addition of H\textsubscript{2} to form an observed dihydride complex [Ir('Pr-PONOP)(H\textsubscript{2})(η\textsuperscript{5}-COD)][BAr\textsubscript{4}\textsuperscript{F}] from which H\textsubscript{2} and COE (the latter formed from slow hydrogenation of COD) must bind competitively compared with COD. Further hydrogenation of COE or COD to cyclooctane (COA) takes much longer (3 d, 4 bar H\textsubscript{2}), after which time only the pale yellow complex 2 and COA are observed.

Attempts to isolate complex 2 at the end of reaction by recrystallization led to the formation of intractable oils, while removal of the H\textsubscript{2} atmosphere resulted in the reversible loss of bound H\textsubscript{2} (vide infra). Characterization was thus performed in situ under a H\textsubscript{2} atmosphere. Complex 2 has a highly fluxional
manifold of hydride ligands. At 298 K a single slightly broadened resonance is observed in the $^1H$ NMR spectrum, $\delta = -8.79$, that integrates to 4 H. This chemical shift is very similar to that reported for $[\text{Ir}(\text{Bu-POCOP})\text{H}_2][\text{BAR}^4_2]$, $\delta = -8.9$, which is also highly fluxional. $^3$ Dissolved H$_2$ is also observed as a broadened signal, suggesting a slow exchange occurs with 2 at room temperature. In the $^{31}\text{P}[^1\text{H}]$ NMR spectrum a single environment is observed at $\delta = 181.2$. Spin-lattice relaxation time ($T_1$) measurements $^{33}$ (500 MHz) on the hydride signal showed that, at 295 K $T_1 = 119 \pm 8$ ms, while at 253 K $T_1 = 38 \pm 1$ ms. At the low temperature the hydride signal is now observed as a sharper triplet [$\delta = -8.81$, $J(\text{PH}) = 7.5$ Hz] and still close to relative integral 4 H. The fluxional behavior and the short $T_1$ time at 253 K suggest rapidly interconverting isomers that sit on a rather flat potential energy surface, for which there is a significant contribution to the time-averaged structure from complexes with a dihydrogen ligand rather than an Ir(V) tetrahydride. Similar behavior has been studied in detail for Ir(η$^2$-POCOP)H$_4$ ($T_1 = 110$ ms) and Ir(η$^2$-PCP)H$_4$ ($T_1 = 130$ ms) but where a significant contribution from a Ir(V) tetrahydride is suggested $^{34}$.

Replacing the H$_2$ atmosphere over complex 2 with D$_2$ resulted in the disappearance of the hydride signal at $\delta = -8.79$ in the $^1H$ NMR spectrum and the observation of HD$_2$ (dissolved) at $\delta = 4.55$ [triplet, $J(\text{HD}) = 43$ Hz]. This confirms intermolecular exchange with D$_2$ and that subsequent intramolecular H/D exchange between the hydrides is occurring, either by a $\sigma$-CAM ($\sigma$-complex assisted metathesis) process or a Ir(V)-tetrhydride. $^{15-37}$ In the $^1H$ NMR spectrum a broad signal is observed at $\delta = -8.8$.

In the absence of an H$_2$ atmosphere complex 2 slowly (3 h) loses H$_2$ in CD$_2$Cl$_2$ solution to form 16-electron $\sigma$-amine-borane complex, $[\text{Ir}(\text{Pr-POCOP})\text{H}_2](\eta^1$-$\text{H}_2$-$\text{B}$-$\text{NMMe}_3$)$][\text{BAR}^4_2]$, 4, Figure 1. This process can be accelerated by freeze/pump/thawing. In the resulting $^1H$ NMR spectrum a single broad hydride environment is observed at $\delta = -19.82$, for which $T_1$ measured at 295 K is fully consistent with a classical dihydride structure (1870 ± 10 ms). $^{33,35}$ These data can be compared with those for the closely related dihydride $[\text{Ir}(\text{Bu-POCOP})\text{H}_2][\text{BAR}^4_2]$ ($\delta = -25.07$, $T_1(\text{min}) = 873$ ms) $^{35}$.

The behavior of the $[\text{Ir}(\text{Pr-POCOP})\text{H}_4]^+$ cation was also studied with density functional theory (DFT) calculations (see the Supporting Information for details) that identified $[\text{Ir}(\text{Pr-POCOP})(\eta^2$-$\text{H}_2)(\text{H})_2]^+$ with cis-hydrides (i.e., Figure 1) as the most stable form. The alternative trans isomer (with $\eta^1$-$\text{H}_2$ trans to N) corresponds to a transition state for intramolecular H/H(D) exchange that proceeds with a barrier of 11.1 kcal/mol. Dissociation of H$_2$ from 2 entails a barrier of 9.6 kcal/mol and forms square-pyramidal 4 with an axial hydride, at +1.4 kcal/mol, consistent with facile intermolecular H$_2$/D$_2$ exchange but endergonic H$_2$ loss that should still be possible upon application of a vacuum. Hydride exchange in 4 is computed to be extremely facile and proceeds via a C$_2$-symmetric dihydride isomer, 4', that lies only 2.9 kcal/mol above 4, consistent with the symmetric structure suggested by $^1H$ NMR spectroscopy. $^{38}$

While we were unable to structurally characterize complex 4, it reacts rapidly with H$_2$B-NMMe$_3$ to quantitatively form an 18-electron $\sigma$-amine-borane complex, $[\text{Ir}(\text{Pr-POCOP})\text{H}_2](\eta^1$-$\text{H}_2$-$\text{B}$-$\text{NMMe}_3$)$][\text{BAR}^4_2]$, 5, Figure 1, for which small number of colorless cuboid crystals were obtained from a CD$_2$Cl$_2$/pentane recrystallization, allowing for a single-crystal X-ray diffraction study. The resulting solid-state structure shows a pseudo-octahedral Ir(III) complex, with two cis hydride ligands (located, but not freely reoriented), a PONOP ligand, and an $\eta^1$-coordinated H$_2$B-NMMe$_3$ ligand. The latter coordination mode is signaled by a long Ir$-$B distance [2.771(4) Å] and a rather open Ir$-$H$-$B angle [134(1)$^\circ$]. $^13$ Structurally characterized complexes with $\eta^1$-coordination modes of amine-boranes $^{19-42}$ have been previously reported. The solution NMR spectroscopic data (CD$_2$Cl$_2$) are fully consistent with the solid-state structure. Two Ir$-$hydride environments are observed in the $^1H$ NMR spectrum, at $\delta = -20.01$ (td) and $-15.91$ (td), and a broad, relative integral 3 H, signal at $\delta = -2.20$ is assigned to the Ir$-$H$_2$ group that is undergoing rapid site exchange between terminal and bridging B$-$H groups. $^4$ The $^1H$ and $^3$P$[^1H]$ NMR spectra of complex 5 are unremarkable.

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**Scheme 3. Synthesis of Complex 2**

![Scheme 3](https://example.com/scheme3.png)

$^{[\text{BAR}^4_2]}$ anions are not shown.

**Figure 1.** Synthesis of and solid-state structure of complex 5. Displacement ellipsoids are shown at the 50% probability level. Selected bond lengths (Å) and angles (deg): Ir$-$P1, 2.2621(7); Ir$-$P2, 2.2660(6); Ir$-$N1, 2.103(2); Ir$-$B 2.771(4); Ir$-$H1C$-$B, 134(1). $[\text{BAR}^4_2]$ anions are not shown.

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2.2. Synthesis of Ir(Pr-PONOP)(propene)[BARF₄] in Solution. Addition of excess propene to in situ generated, pale yellow, complex 2 resulted in the immediate formation of the alkene dihydride complex [Ir(Pr-PONOP)H₂(η²-propene)]-[BARF₄], 7, Scheme 4. While the onward reaction of 7 is slow (see Section 2.3 for characterization and reactivity), simply pumping a solution to dryness results in H₂ loss and the formation of [Ir(Pr-PONOP)(η²-propene)][BARF₄], 6. Complex 6 thus formed can be isolated in crystalline form in 94% yield from a subsequent 1,2-difluorobenzene/pentane recrystallization. Analogous Ir(Bu-PCP)(propene) and Ir(Bu-PONOP) complexes are known.⁴³,⁴⁴

In CD₂Cl₂ solution a single set of resonances for the propene ligand are observed in the ¹H and ¹³C(¹H) NMR spectra of complex 6, alongside four closely overlapping Pr methyl, two methine, and two pyridyl environments, the last in a 1:2 ratio. A single environment is observed in the ¹³P(¹H) NMR spectrum, δ 188.6. These solution data point to a fluxional process for the propene that gives time-averaged C₂ symmetry on the NMR time scale. This process is not frozen out at 183 K; that is, a single ⁴³P environment is still observed. A simple rotation around the (C=C)−Ir−N vector accounts for this,⁴⁵ as also suggested for complex 1.

2.3. Addition of H₂ to [Ir(Pr-PONOP)(propene)][BARF₄] in Solution, and Characterization of [Ir(Pr-PONOP)H₂(propene)][BARF₄]. With the synthesis of complex 6 in hand its reactivity with H₂ in CD₂Cl₂ solution was studied to determine baseline solution reactivity for comparison with the solid state. Addition of H₂ (4 bar) to orange complex 6 rapidly (on time of mixing) resulted in the formation of a pale yellow solution that contains dihydride propene complex 7, alongside dihydrogen/dihydride 2 and dissolved propene, all in approximately equal amounts, Scheme 5. Over the course of 3 d under H₂ this mixture slowly turns to give complex 2 and propene as the only components. As for the COD complex 1 these observations are best accounted for by competitive binding of propene (i.e., complex 7) and H₂ (complex 2). Evidence for an equilibrium between 2 and 7 is provided by the addition of H₂ to a solution of complex 6, shaking the NMR tube to ensure reaction with H₂ to form 7, and then removal of noncondensable gases (H₂) from a frozen (77 K) solution under vacuum. Under these conditions of low H₂ concentration but persistent propene, complex 7 is the sole organometallic product observed on thawing under Ar. This also allows for its definitive characterization free from other products.

In CD₂Cl₂ solution (Ar atmosphere, 298 K) the ¹³C(¹H) NMR spectrum of complex 7 displays two alkene environments (δ 82.5, 62.0). In the ¹H NMR spectrum sharp signals for two inequivalent Ir−H groups, at δ −11.64 and −16.50, that also show coupling to two ³¹P nuclei are observed alongside a single set of resonances due the bound propene. The Pr methyl groups resolve as at least five broad signals, and the methine signals are also complex. These data report on cis-hydride environments, with the propene in an axial coordination site. Two tightly coupled AB doublets are observed in the ³¹P(¹H) NMR spectrum at δ 168.2 and 170.0 that show trans PP coupling [J(PP) = 320 Hz]. Inequivalent phosphine environments are expected for propene coordinated via a π-face in the axial position that is not undergoing reversible dissociation that is fast on the NMR time scale. At low temperature (185 K) the ³¹P(¹H) NMR spectrum becomes significantly more complex, suggesting the resolution of two different isomeric species associated with the orientation of the propene ligand, which is undergoing fast rotation at room temperature. Two sets of hydride resonances are now observed at chemical shifts consistent with their frequency averaging at room temperature.

Under an Ar atmosphere in a sealed NMR tube complex 7 does not lose H₂ in solution. However, as stated, pumping to dryness results in the reformation of 6, showing that H₂ addition is reversible, but its loss is likely an endergonic process. Over a 24 h period decomposition occurs in solution (~25%) to unidentified products, and attempts to recrystallize led to poorly structuring crystalline material from which no structural solution was possible.

DFT calculations confirm the facile addition of H₂ to 6 to form 7 (ΔG° = 15.9 kcal/mol; ΔG° = −4.4 kcal/mol, Figure 2) and that this reaction, with a return barrier of 20.3 kcal/mol, should be reversible if H₂ is removed from the system. In contrast, the onward hydrogenation of propene from 7 is much less accessible due to the significant barriers associated with the propene migratory insertion step. The lowest-energy process is shown in Figure 2 and has an overall barrier of 24.8 kcal/mol via TS(7→8iso)M, consistent with a slow process at room temperature. TS(7→8iso)M leads to an isopropyl intermediate, 8iso, and geometrically this step is best described as a hydride migration onto the propene ligand (labeled “M”) that is coupled to movement of the spectator hydride such that the isopropyl ligand occupies the axial site in 8iso as the Τₐₖₛḷ isomer. A second pathway where propene inserts (labeled “I”)
into the adjacent Ir–H bond proceeds via TS(7−8veral)I at +26.0 kcal/mol and leads to the more stable T1H isomer of 8veral at −0.2 kcal/mol. Hydride migration and propene insertion transition states to form the n-propyl species (8veral) were also located (TS(7−8veral)M: +21.9 kcal/mol; TS(7−8veral): 24.7 kcal/mol) and gave the Talkyl and T1H isomers of 8veral at +4.3 kcal/mol and −3.1 kcal/mol, respectively (see the Supporting Information). All these migratory insertion transition states exhibit “late” geometries; for example, in TS(7−8veral)M the forming C–H and Ir–Calkyl bonds (1.21 Å/2.19 Å) are already close to their computed values in Talkyl 8veral (1.10 Å/2.15 Å). The high barriers to insertion are likely linked to the formation of a strongly donating alkyl ligand trans to the spectator hydride, although movement of the spectator hydride ligands does serve to mitigate this effect (the H−Ir–Calkyl angle is ca. 140° in all cases).

Once formed, Talkyl 8veral must first isomerize to T1H 8veral in order to access C–H reductive coupling via TS(8veral−9veral) (+10.6 kcal/mol) to give the propane complex 9veral (+6.8 kcal/mol). The reaction is then driven to completion by displacement of propane by either propene (ΔG° = −19.8 kcal/mol relative to 6) or (if present) H2 to give 2 (ΔG° = −14.7 kcal/mol). The calculations thus indicate the equilibrium between 2 (+ propene) and 7 (+ H2) will favor the latter (ΔG = −5.1 kcal/mol) while 2 is still accessible under H2 pressure.

### 2.4. SC-SC Reactivity in the Solid State

In contrast to the solution behavior, addition of H2 to finely crushed crystalline samples of complex 6 (~50 mg, 15 min, 4 bar) did not result in the formation of tetrahydride complex 2 or the hydrogenation of propene to propane, even after 5 d under H2. Instead room-temperature 31P{1H}/31C{1H} solid-state NMR (SSNMR) and solution (CD2Cl2) spectroscopy of dissolved crystalline material showed the formation of the dihydride alkene complex [Ir(Pr-PONOP)H2(η2-propene)][BAr4]+, 7, with data identical to those obtained by solution methods. Under a system open to Ar, in the solid-state complex 6 loses H2 to reform 6, a process that is speeded up by application of a dynamic vacuum (2 h). No decomposition is observed, unlike in solution. Because of the experimental challenges of keeping samples under a H2 atmosphere when manipulating in the solid state, these samples show 90% complex 7 with the remainder being complex 6. Analysis of single crystals of complex 7 hydrogenated ex situ in the bulk, by rapid transfer to the diffractometer, leads to a structural refinement in which the electron density due to the alkene ligand could not be satisfactorily modeled, a consequence of partial H2 loss to reform complex 6. Analysis of material that had completely reformed complex 6 after H2 loss showed only weak Bragg peaks and showed evidence of significant crystal cracking (scanning electron microscopy (SEM), Supporting Information). As the resulting 31P{1H} SSNMR spectrum of this...
material was indistinguishable from initially synthesized complex 6, this suggests retention of short-range order but loss of bulk crystallinity. The formation of microcrystalline, or amorphous, products as a response to solid-state reactivity in single crystals is well-documented. To circumvent this problem of H$_2$ loss in complex 7 we used in situ SC-SC techniques on the 119 Beamline at the Diamond Light Source for its synthesis from 6. This allowed for the collection of data under an atmosphere of H$_2$ and thus the formation of complex 7 without reforming 6. The solid-state structure of complex 6 is shown in Figure 2. Data were collected at 273 K allowing for the subsequent reaction with H$_2$ to be followed crystallographically in situ. The structural solution is good [R(2σ) = 4.0%, R$_{int}$ = 4.3%, P1 space group] and shows a pseudo-square-planar cation, as expected for an Ir(1) complex. The propene is disordered essentially equally between two sites, related to one another by a noncrystallographic mirror plane (inset left Figure 2 and Figure 3), accounted for by coordination of a different π-face of propene in each. The C–C distances in the propene are consistent with a double and a single bond [1.271(8) and 1.56(1) Å, respectively]. The Ir–C distances show alkene coordination with a non-interacting methyl group: Ir–C1, 2.138(5); Ir–C2; 2.209(5); Ir–C3, 3.15(5) Å. Data collection at 150 K on a laboratory-based diffractometer (Cu source), while more precise [R(2σ) = 1.9%, R$_{int}$ = 2.0%], showed the same disorder indicating that there are no dynamic processes operating in the solid state that involve reorientation of the propene. The supporting [BAr$_4^-$] anions present a skewed-bicapped square prism motif, in which 10 anions surround two crystallographically identical cations. This is discussed in more detail in Section 2.6.

Addition of H$_2$ (2 bar) to the same single crystal used for the structural analysis of complex 6 at 273 K led to the formation of complex 7, for which a satisfactory structural solution could be determined, Figure 3 [R(2σ) = 9.3%, R$_{int}$ = 8.7%, P1 space group]. However, there was a significant deterioration in data quality on hydrogenation resulting in a drop in resolution from 0.65 Å in 6 to 1.2 Å for 7. Complex 7 has a pseudo-octahedral coordination geometry, in which the propene has moved from the equatorial position found in 6 to an axial position. The remaining coordination sites are occupied by the hydrides, which were not located, but their presence is confirmed by solution NMR spectroscopy on dissolved crystals. In this SC-SC transformation the disorder observed in the propene ligand in 6 is retained in complex 7, with two orientations observed, in an ~50:50 ratio, Figures 3 and 4. Because of the lower quality of data the C–C and C=C–C distances in the propene were restrained to sensible distances [1.46(6), 1.31(8) Å, respectively], and detailed discussion of the metrics of propene binding are not appropriate. Confidence in the assignment of C=C–C and C=C–C bonds comes from the orientation of the disordered propene fragments that map onto those observed in starting 6, the longer Ir–C distance to the third propene carbon atom [Ir–C3A, 3.29(4) Å], and solid-state NMR data that support the formation of two isomers, as discussed next.

2.5. Solid-State NMR Analysis of Complexes 6 and 7. In the $^{31}$P($^1$H) SSNMR spectrum of complex 6 two $^{31}$P environments are observed [δ 189.5, 194.1], as an AB doublet showing large $^{31}$P–$^{31}$P coupling, consistent with trans-disposed, crystallographically distinct, phosphines, J(PP) = 310 Hz. While the two, noncrystallographically generated, disordered components observed in the solid-state structure suggest there should be four $^{31}$P environments, we suggest a coincidence of signals results in only two being observed. In contrast, in the $^{13}$C($^1$H) NMR spectrum four signals are observed in the bound alkene region [δ 57.4, 56.6, 44.8, 42.9], fully consistent with the solid-state structure. In the $^{31}$P($^1$H) SSNMR spectrum of complex 7 a complex set of overlapping resonances is observed, centered around δ 174, while in the $^{13}$C($^1$H) SSNMR spectrum two sets of alkene signals are observed. These data are consistent with two isomers being formed for complex 7 in the solid state, leading on from the two isomers observed for propene binding in complex 6 that are related by the relative orientation of the methyl group.

2.6. Movement of the PONOP-Ligand on the SC-SC Transformation. Oxidative addition of H$_2$ to complex 6 results in the alkene in 7 now being orientated orthogonal to its starting position, Figures 3 and 4. We initially interpreted this as coming from movement of the alkene ligand around the coordination sphere of the iridium in the SC-SC transformation. However, inspection of the wider crystalline environment of [BAr$_4^-$] anions surrounding the cationic metal center shows that, surprisingly, it is the Pr-PONOP ligand that moves on oxidative addition of H$_2$, not the alkene. Figure 5A shows that the [BAr$_4^-$] anions in 6 form a skewed bicapped square prism (BCSP) that surrounds two crystallographically related [Ir(Pr-PONOP)H$_2$($^1$η$^3$-propene)]$^+$ cations. BCSP motifs have been reported previously in SMOM chemistry. The cations are orientated so that the propene is directed into a pocket formed by three of the [BAr$_4^-$] aryl groups of a single anion, with the pyridyl group directly trans to the propene. On addition of H$_2$ in the SC-SC transformation the skewed BCSP motif is retained (difference in unit cell volumes = 1.9%), but there is a small contraposition of the [BAr$_4^-$] anions in upper and lower basal planes. The orientation of the propene is also retained in the same pocket of aryl groups. What has changed significantly is the orientation of the PONOP ligand, which has pivoted ~90° around the P–Ir–P vector so that it now sits orthogonal to the propene. Figure 5B,C shows this schematically and by an overlay of the crystallographically determined structures, respectively. While such large movements of metal–ligand fragments on SC-SC transformations are preceded, they are rare. In the case here, this reorientation may explain why the crystal quality degrades significantly on cycling H$_2$ addition/removal, that is, 6-7-6. The addition of H$_2$ to 6 to form 7 also results in a change in the oxidation state of the metal, accompanied by a move from pseudo square planar to octahedral. SC-SC transformations that involve an overall change in oxidation state have been reported previously, for example, Mn(II)/Mn(IV). Co-
(II)/Co(III),\textsuperscript{61} Rh(I)/Rh(III),\textsuperscript{13,62,63} Ir(I)/Ir(III),\textsuperscript{21} Ir(III)/Ir(V),\textsuperscript{64} and Au(I)/Au(III).\textsuperscript{55}

\textbf{2.7. Differences between Solution and Solid-State Reactivity.} That the dihydrogen/dihydride complex 2 is formed in solution on hydrogenation of complex 6 while only complex 7 formed in the solid-state could arise from two restraining conditions imposed by the crystalline microenvironment of [BAR\textsubscript{4}]\textsuperscript{−} anions. First, the reversible dissociation of propene from complex 7 that occurs in solution on addition of H\textsubscript{2} is clearly disfavored in the solid state. Second, onward reactivity of the propene hydride to ultimately form free propane, by migratory insertion and reductive elimination, and 2 could be disfavored due to local steric effects of the proximal [BAR\textsubscript{4}]\textsuperscript{−} anion that hinder either of these transformations. In both solid state and solution complex 7 undergoes H\textsubscript{2} loss to reform 6. We thus turned to computational studies in the extended solid state to understand these fundamental steps in greater detail and compare with solution DFT studies on the molecular cations reported above.

\textbf{2.8. Computational Studies in the Solid State.} The structures of 6 and 7 in the extended solid state were computed with periodic DFT calculations using the PBE-D3
functional. Geometries for both species were based on the experimental crystal structures, and subsequent reactivity studies considered changes at one of the two Ir centers present in each unit cell (see the Supporting Information for full details). Key stationary points are presented in Figure 6, where the profile in red is computed using the unit cell of 6, while that in blue uses the unit cell of 7.

H₂ addition to 6 to form 7 has a computed free energy change of −4.8 kcal/mol, indicating that, while 7 is favored thermodynamically, 6 may still be accessible from 7 under conditions of H₂ loss. Kinetically, however, H₂ loss directly from 7 is inaccessible with a barrier of 44.1 kcal/mol; the extended crystal environment within 7 therefore blocks this process. In contrast, H₂ oxidative addition to 6 is feasible (ΔG° = +14.4 kcal/mol) and forms a propene dihydride complex within the crystal environment of 6. This species, 7*, is 10.9 kcal/mol less stable than 7, and we propose that one reason for this arises from the movement of the propene ligand to outside the pocket defined by the adjacent [BAR³⁺]²⁺ anion (represented by the open “V” in Figure 6) that occurs upon H₂ addition. On the basis of the experimentally observed, reversible H₂ addition to 6 to give 7, we speculate that the reorganization of the crystal lattice (that occurs with the net movement of the pincer ligand relative to the anionic framework) must occur at 7* to move between the “red” (7*) and “blue” (7) crystal lattices. Viewed in reverse, and assuming facile rearrangement between the two crystal lattices, the loss of H₂ from 7 can occur with an overall barrier of 19.2 kcal/mol via TS(6−7*).

The positioning of the propene relative to the [BAR³⁺]²⁺ anion pocket appears to be a key factor in determining the energy of other stationary points in these systems. Thus, in 6* the propene sits outside the pocket, and this structure is 16.3 kcal/mol higher than that of 6. Similarly, H₂ reductive elimination from 7 is also strongly disfavored, as this requires the propene to move out of the pocket in order to restore square-planar coordination at the Ir(I) center in 6*. The preferred pathways for propene migratory insertion are also impacted by the crystal environment. Thus, for 7 the hydride migration pathway is favored via TS(7−8inv)M at +21.2 kcal/mol, as this allows the propene to remain in the anion pocket. For 7* alkene insertion into the hydride bond via TS(7*−

3. CONCLUSIONS
While still relatively uncommon, organometallic synthesis and reactivity in the single-crystalline environment is becoming an increasingly appreciated methodology.⁶¹ However, examples where solution and crystalline-phase reactivity can be directly compared experimentally⁶⁸ and computationally are rare, in part a consequence of the stabilizing role that the solid state has on reactive complexes that are challenging to access in solution (e.g., σ-alkane complexes⁶⁷). With [Ir(Pr-PONOP)−(η⁵-propene)][BAR³⁺] we have such a platform through reactivity with H₂ to initially form [Ir(Pr-PONOP)(η⁵-propene)H₂][BAR³⁺]. Subsequent migratory insertion and reductive elimination of propane occurs in solution but in the solid state does not. While the solution-phase chemistry is more complex than that observed in the SC-SC transformation, with equilibria operating through reversible alkene dissociations that are not available in the solid state, the solid-state crystalline microenvironment, and, in particular, the positioning of the propene ligand relative to the [BAR³⁺]²⁺ aryl groups, is a key factor in determining both the relative (higher) barrier to migratory insertion and the observed structures. The significantly more stable arrangement when propene sits in the pocket formed by the aryl groups in the crystalline lattice leads to both Pr-PONOP ligand movement and plasticity in the anion lattice to accommodate this motif on reaction of 6 with H₂ to form 7. While this reorganization provides access to the most stable structures in the solid state, a consequence is that the barriers to onward reactivity (e.g., migratory insertion) are significant, meaning that the targeted complex that has propane interacting with the Ir center is not accessible via this route. What will be interesting to explore is if engineering both the anion-motif and metal−ligand fragment in related SMOM systems allows for a reduction in these barriers through ground-state destabilization and/or transition-state stabilization.⁶⁹ These are concepts that are familiar in enzyme catalysis, where the primary, secondary, and tertiary structures also work in concert to lower barriers to elementary reaction steps.⁷⁰

ASSOCIATED CONTENT
Supporting Information
The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.organomet.2c00274.

Full experimental details, synthesis of new complexes, spectroscopic data, details of in situ X-ray diffraction experiments, and computational studies (PDF)

Cartesian coordinates of the DFT calculated structures (XYZ)
Accession Codes
CCDC 2175292–2175295 contain the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/data_request/cif, or by emailing data_request@ccdc.cam.ac.uk, or by contacting The Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; fax: +44 1223 336033.

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Notes
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■ DEDICATION

Dedicated to Professor Maurice Brookhart (Brook) for his immense contributions to organometallic synthesis and catalysis, and his generosity and support of others in the field.

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