Intermolecular C-H activation with an Ir-METAMORPhos piano-stool complex: multiple reaction steps at a reactive ligand

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Substrate activation by means of a reactive ligand is a topic of much interest. Herein we describe a stoichiometric anti-Markovnikov C–N bond formation involving ligand reactivity in multiple steps along the reaction coordinate, including ligand assisted substrate (de)protonation and C–N bond formation, as illustrated by a combined experimental, spectroscopic and computational study. This affords a highly unusual four-membered iridacycle bearing an exo-cyclic C–C double bond.

Metal-ligand bifunctional substrate activation has recently evolved as a valuable strategy in homogeneous catalysis. Hydrogen-bond interactions and acid–base reactivity are often-encountered strategies in this context.1,2 Prime examples of reactive ligands with internal Brønsted-active sites that can undergo reversible deprotonation are those containing primary or secondary amines. The nitrogen atom may be in the coordination sphere of the transition metal or located in the ligand backbone, having no direct interaction with the metal.3 C–H activation remains to be a topic of intense research, with a major focus on site-specific and regioselective functionalization. Intramolecular ligand-assisted metal-mediated C–H activation, via a directing group, is frequently utilized4 but intermolecular C–H activation facilitated by a reactive ligand (Fig. 1) that functions as a valuable strategy in homogeneous catalysis. Hydrogen-bonding properties upon coordination to transition metals. 10

However, elegant work by Grotjahn using imidazolylphosphines as reactive ligands to enhance alkyne C–H activation has demonstrated the feasibility of this approach for the hydration of alkynes.6 The related hydroaddition of amines to unsaturated hydrocarbons is an attractive and atom-efficient protocol to form C–N bonds. Hydroamination with late transition metal complexes typically proceeds via initial coordination and activation of the hydrocarbon, with follow-up (external) nucleophilic attack of the (activated) amine and proton transfer.7 Examples where C–H activation of an unsaturated hydrocarbon precedes the overall syn-addition of an amine are rare8 and no structurally characterized complex has been reported, to the best of our knowledge. We hypothesized that metal–ligand bifunctional activation of a hydrocarbon could allow for direct observation of this unusual pathway, which could potentially open up new avenues for hydroaddition chemistry and catalysis. Ligands that combine more than one type of reactivity in the scaffold are uncommon9 but these designs could provide entry into site-selective activation and functionalization of substrates.

Sulfonamidophosphine ligands (coined METAMORPhos), which are accessible from commercially available sulfonamides and chlorophosphine precursors, have been demonstrated to combine proton responsive character at nitrogen with hydrogen bonding properties upon coordination to transition metals.10 Intermolecular C–H activation mediated by this ligand scaffold has not been observed to date. METAMORPhos contains two potentially reactive ligand sites, namely the sulfonyl oxygen and the nitrogen, of which the former can coordinate to metal ions (both as neutral or anionic donor), while the latter is part of the second coordination sphere. Iridium piano-stool complexes have been used regularly for a number of bond activation processes, including the use of noninnocent ligands in the coordination sphere of Ir.11 Herein, we demonstrate the key steps of METAMORPhos-assisted C–H activation of alkynes in the coordination sphere of Ir11 and subsequent overall syn-addition of the H–N(R) ligand fragment over the C≡C bond. The end-product contains a unique four-membered metallacycle with an exo-cyclic double bond,
confirmed by X-ray crystal structure determination and NMR spectroscopy. DFT calculations provide insight in the pathway for this unusual transformation.

Mixing two molar equivalents of ligand \( 1^- \) with Ir-precursor \([\text{IrCl}(\text{Cp}^*)(\mu-\text{Cl})]_2\) in \( \text{CD}_2\text{Cl}_2 \) instantly led to complete consumption of starting materials and formation of a single species, which was characterized by multinuclear NMR spectroscopy and HR-MS spectrometry as neutral P-coordinated complex 2 (see Scheme 1). An X-ray crystal structure determination supports this conformation in the solid state (Fig. 2, left). Hydrogen bond interactions between the N–H of the METAMORPhos ligand and the chloride ligands \( \text{Cl}_1 \) and \( \text{Cl}_2 \) were observed \( [\text{N}_1\cdots\text{Cl}_1 \ 3.1451(13), \text{N}_1\cdots\text{Cl}_2 \ 3.2529(14)] \) (see Table S1 in the ESI).

Addition of 2 to a suspension of sodium acetate (NaOAc) in \( \text{CH}_2\text{Cl}_2 \) at room temperature led to complete conversion of this complex to a new species 3 (as could easily be observed by \( ^{31}\text{P} \) NMR spectroscopy), formulated as \( \text{IrCl}(\text{Cp}^*)(\kappa^2-\text{P},\text{O},\text{Ir}) \) (see Scheme 1), based on multinuclear NMR spectroscopy and HR-MS spectrometry and supported by single crystal X-ray structure determination (Fig. 2, right). Compared to the bond lengths found in the precursor species 2, the \( \text{N}_1\cdots\text{S}_1 \) bond is shortened (1.5464(13) Å) while the \( \text{S}_1\cdots\text{O}_2 \) bond (1.5098(11) Å) is indeed undergone deprotonation.

Selected bond lengths (Å) and angles (°) for: 2 \( \text{Ir}_1–\text{P}_1 \ 2.2838(4); \text{Ir}_1–\text{Cl}_1 \ 2.3956(4); \text{Ir}_1–\text{Cl}_2 \ 2.4061(4); \text{P}_1–\text{N}_1 \ 1.7019(13); \text{N}_1–\text{S}_1 \ 1.6535(13); \text{S}_1–\text{O}_1 \ 1.4351(12); \text{S}_1–\text{O}_2 \ 1.4358(13); \text{N}_1–\text{Cl}_1 \ 3.1451(13); \text{N}_1–\text{Cl}_2 \ 3.2529(14); \text{N}_1–\text{H}_1\text{N}–\text{Cl}_1 \ 119.8(19); \text{N}_1–\text{H}_1\text{N}–\text{Cl}_2 \ 115.9(19). \) For 3 \( \text{Ir}_1–\text{P}_1 \ 2.2968(4); \text{Ir}_1–\text{Cl}_1 \ 2.1630(10); \text{Ir}_1–\text{Cl}_2 \ 2.3981(4); \text{P}_1–\text{N}_1 \ 1.6535(13); \text{N}_1–\text{S}_1 \ 1.5464(13); \text{S}_1–\text{O}_1 \ 1.5098(11); \text{S}_1–\text{O}_2 \ 1.4448(11); \text{P}_1–\text{Ir}_1–\text{O}_1 \ 80.41(3). \)

With pre-activated species 3 in hand, we decided to investigate the ligand assisted intermolecular activation of alkynes, generating an Ir-phenylacetylide species via proton transfer from the terminal alkyne to the proton responsive ligand, which might allow for alternative reaction pathways in the context of selective hydrogenolitization. Addition of phenylacetylene to 3 led to the formation of a new species \( (1^\text{H} \text{NMR}: \delta 3.10 \text{ ppm}) \) after two hours at 50 °C. The \( 1^\text{C}(1^\text{H}) \) NMR spectrum showed no formation of the anticipated \( \text{Ir}^{III}(\text{C} \equiv \text{C} \text{Ph}) \) complex 5 (Scheme 2), but did reveal an unexpected doublet at 114.06 ppm \( (J_{\text{C}–\text{H}} = 11.7 \text{ Hz}, \text{CH}) \), while the corresponding \( 1^\text{H} \) NMR spectrum showed a singlet at 6.88 ppm. The identity of the complex obtained could be determined via single crystal X-ray structure determination, obtained via slow diffusion of pentane into a THF solution of complex 4. The resulting X-ray structure establishes the formation of an Ir-vinyl complex containing an unusual four-membered Ir-P-N-C ring, see Fig. 3.

The Ir–P–N–C ring is essentially flat, with a torsion angle \( \angle \text{Ir}_1–\text{P}_1–\text{N}_1–\text{C}_1 \) of \(-3.13^\circ\). The geometry of the metallacycle is very asymmetric, with bond angles of \( \angle \text{P}_1–\text{Ir}_1–\text{C}_1: 69.21(9)^\circ, \angle \text{Ir}_1–\text{P}_1–\text{N}_1: 88.48(9)^\circ, \angle \text{P}_1–\text{N}_1–\text{C}_1: 100.26(19)^\circ \) and \( \angle \text{N}_1–\text{C}_1–\text{Ir}_1: 101.91(19)^\circ \). Compared to complex 3, the P-N bond lengths are slightly elongated \( (\text{P}_1–\text{N}_1: 1.6535(13), \text{P}_1–\text{N}_1: 1.717(3) \text{ Å for 3 and 4 respectively}) \). The \( \text{N}_1–\text{S}_1 \) bond length of 1.653(3) Å clearly points toward an N–S single bond, while the \( \text{C}_1–\text{C}_1 \) bond length of 1.338(5) Å indicates a C–C double bond. To the best of our

![Figure 2](image-url)  
**Fig. 2** Left: X-ray crystal structure of 2. Right: X-ray crystal structure of 3. Selected bond lengths (Å) and angles (°) for: 2 \( \text{Ir}_1–\text{P}_1 \ 2.2838(4); \text{Ir}_1–\text{Cl}_1 \ 2.3956(4); \text{Ir}_1–\text{Cl}_2 \ 2.4061(4); \text{P}_1–\text{N}_1 \ 1.7019(13); \text{N}_1–\text{S}_1 \ 1.6325(13); \text{S}_1–\text{O}_1 \ 1.4351(12); \text{S}_1–\text{O}_2 \ 1.4358(13); \text{N}_1–\text{Cl}_1 \ 3.1451(13); \text{N}_1–\text{Cl}_2 \ 3.2529(14); \text{N}_1–\text{H}_1\text{N}–\text{Cl}_1 \ 119.8(19); \text{N}_1–\text{H}_1\text{N}–\text{Cl}_2 \ 115.9(19). \) For 3 \( \text{Ir}_1–\text{P}_1 \ 2.2968(4); \text{Ir}_1–\text{Cl}_1 \ 2.1630(10); \text{Ir}_1–\text{Cl}_2 \ 2.3981(4); \text{P}_1–\text{N}_1 \ 1.6535(13); \text{N}_1–\text{S}_1 \ 1.5464(13); \text{S}_1–\text{O}_1 \ 1.5098(11); \text{S}_1–\text{O}_2 \ 1.4448(11); \text{P}_1–\text{Ir}_1–\text{O}_1 \ 80.41(3). \)

![Figure 3](image-url)  
**Fig. 3** X-ray structure and schematic representation of 4. Selected bond lengths (Å) and angles (°): \( \text{Ir}_1–\text{P}_1 \ 2.2317(11); \text{Ir}_1–\text{Cl}_1 \ 2.077(3); \text{Ir}_1–\text{Cl}_2 \ 2.4083(8); \text{P}_1–\text{N}_1 \ 1.717(3); \text{N}_1–\text{C}_1 \ 1.468(4); \text{N}_1–\text{S}_1 \ 1.653(3); \text{S}_1–\text{O}_1 \ 1.436(2); \text{S}_1–\text{O}_2 \ 1.430(3); \text{C}_1–\text{C}_2 \ 1.338(5); \text{P}_1–\text{Ir}_1–\text{C}_1 \ 69.21(9)^\circ; \text{Ir}_1–\text{P}_1–\text{N}_1 \ 88.48(9)^\circ; \text{P}_1–\text{N}_1–\text{C}_1 \ 100.26(19)^\circ; \text{N}_1–\text{C}_1–\text{Ir}_1 \ 101.91(19)^\circ \).

![Scheme 2](image-url)  
**Scheme 2** Complex 3 reacts with phenylacetylene to generate Ir-acetylide complex 5, which rearranges to Ir-vinyl complex 4 within 3 hours at 50 °C.
knowledge only three complexes containing a four-membered M–P–N–C ring with an sp² hybridized carbon atom have been reported in literature.¹⁴ This is the first example reported with iridium as well as the first structure that is generated from an alkynyl, making the vinyl fragment a unique exo-cyclic entity. Four-membered M–P–N–C rings wherein C is a divalent carbene are more common in literature, particularly with ruthenium.¹⁵ Alkyne activation likely proceeds by concerted metalation–deprotonation after initial coordination of the π-system to Ir¹⁺, facilitated by Cl⁻ dissociation in THF.¹⁰ Proton-transfer to the more basic sulfonamide nitrogen is favored over protonation of the S–O, but temporary formation of –OH as a kinetic intermediate can not be excluded.¹⁶

Monitoring the unique conversion from 3 to this novel complex 4 by ³¹P{¹H} NMR spectroscopy directly after addition of phenylacetylene at room temperature revealed the intermediary of another species (³¹P NMR: δ 33.1 ppm). In an attempt to characterize this complex, the reaction of phenylacetylene and complex 3 was monitored by ¹H, ³¹P and ¹³C NMR spectroscopy at 0 °C. Signals at 102.70 (d, J = 6.4 Hz, Cₜₐₜ) and 94.86 (s, Cₜₐₜ), in the ¹³C{¹H} NMR spectrum support the involvement of the initially anticipated Ir¹⁺(C≡CPh) species 5 in this reaction (Scheme 2).⁵,⁶,⁸

Complex 4 is proposed to form via initial proton transfer from the phenylacetylene to the METAMORPhos backbone (generating 3), followed by a formal intramolecular anti-Markovnikov hydroamination onto the resulting acetylide species. This selective C–N bond formation, which occurs in an overall syn addition, would involve nucleophilic attack of the nitrogen onto the electrophilic α-carbon of the Ir(C≡CPh) fragment.¹⁷ To support this proposed mechanism, DFT calculations were performed (BP86, def2-TZVP); the energetically most favored energy profile is displayed in Fig. 4 (see ESI† for comparison with experimental metric parameters). The combination of (3 + HCCPh) was used as reference point (0.0 kcal mol⁻¹). Formation of Ir-acetylide complex 5 is slightly downhill by 1.5 kcal mol⁻¹. From this observable intermediate, the most energetically favored pathway to 4 proceeds via initial proton transfer from the N–H of the ligand to the β-carbon of the acetylide through TS₁, which is endergonic by 17.6 kcal mol⁻¹. This generates intermediate Int (13.7 kcal mol⁻¹), wherein the anionic ligand is only monodentate P-coordinated.¹⁸ The calculated HOMO and LUMO of this intermediate species support formulation as an electrophilic iridium(III)-vinylidene (Fig. 5). Subsequent nucleophilic attack of the nitrogen of the ligand onto the α-carbon of the vinylidene via TS₂ (endergonic by 18.3 kcal mol⁻¹) generates complex 4, bearing a unique exo-cyclic vinyl unit. This product is exergonic by 6.7 kcal mol⁻¹ relative to the starting materials. We were unable to find a transition state for the alternative concerted mechanism involving direct N–H σ-addition over the C≡C bond. The pathway involving protonation via a sulfone O–H was found to be slightly higher in energy (initial proton transfer step was endergonic by 18.6 kcal mol⁻¹; see ESI†, Fig. S1) relative to the described pathway. A solvation model (COSMO) did not affect the turnover-limiting step.

In conclusion, we have demonstrated the reactivity of Ir¹⁺ piano-stool complexes with sulfonamidophosphine ligand ¹¹ª (METAMORPhos) for the heterolytic activation of alkynyl C–H bonds. The initially generated species 2, featuring monodentate P-coordination, reacts with exogenous base to generate complex 3, bearing a reactive P,O-coordinated METAMORPhos ligand. In the presence of terminal alkynes, the ligand is reprotonated via PhC≡C–H activation to generate acetylide compound 5. This intermolecular C–H activated species undergoes facile anti-Markovnikov hydroamination reaction in the coordination sphere of Ir¹⁺. This represents a novel reaction mode for this ligand class, making this a versatile design in the context of chemically non-innocent ligand reactivity. The resulting unique four-membered Ir-PNC metallacycle 4, featuring an exocyclic vinyl group, is structurally characterized and DFT calculations support the transient formation of an Ir¹⁺, vinylidene intermediate. The insights presented potentially provide an entry into selective intra- and intermolecular C–H activation protocols with e.g. alkynes.

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Notes and references

† Crystallographic details, for 2: C₉H₇NOCl⁻ÎnrNO₂PS⁻F⁻ = 795.77, orange needle, 0.63 × 0.33 × 0.16 mm³, triclinic, P1 (no. 2), a = 10.16597(16) Å,
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Complex 1 also undergoes intramolecular C–H activation of the benzene moiety of the sulfonamide under H2 (unpublished results).
