Fundamental reactivity of the Metal-Carbon bond in cyclometalated PNC-complexes
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Reversible Cyclometalation at Rh\textsuperscript{I} as Motif for Metal-Ligand Bifunctional Bond Activation and Base-free Formic Acid Dehydrogenation

3.1 Introduction

The application of reactive ligands for metal-ligand bifunctional bond activation and subsequent cooperative catalysis receives much attention, as discussed in Chapter 1. Among the different reactive ligand designs, systems bearing a proton-responsive group (showing reversible deprotonation activity) are particularly attractive and versatile for substrate activation. Generally, two strategies to incorporate such a fragment (an ‘internal base’) within the ligand structure were developed: i) a site in the coordination sphere of a metal center and ii) a site at a location not directly connected to the metal center (2nd coordination sphere). Well-known designs implementing the latter strategy operate via reversible dearomatization by deprotonation of functionalized picoline, aminopyridine, or pyridone fragments. Regarding the strategy encompassing proton-responsive groups in the coordination sphere of a transition metal, reversible deprotonation of metal-bound functionalized amines has been successfully applied in a variety of catalytic transformations.

Metal-carbon bonds are typically rather strong, but the bond energy can be influenced by e.g. strain or non-ideal orbital overlap, as present in cyclometalated species. Reversible cyclometalation at late transition metals using strong acids has been well-documented for stoichiometric reactions but examples with low-valent metal ions such as Rh\textsuperscript{I} and applications of this type of reactivity in catalytic turnover are rare, to the best of our knowledge (see previous Chapters). Metal-ligand bifunctional catalysis by reversible cyclometalation has been postulated as possible mechanism with a few systems. Mashima et al. discussed this strategy for the dehydrogenative silylation of phenylpyridines catalyzed by a cyclometalated iridium complex. A similar ‘roll-over’ mechanism was suggested for the base-free transfer hydrogenation with a ruthenium catalyst. The cooperativity of a cyclometalated fragment in the ligand
structure has also been proposed, on the basis of computational studies, to be suitable for the dehydrogenation of ammonia-borane.\textsuperscript{28–30} However, it was experimentally proven that this mechanism occurs most likely only in the early stage of catalysis\textsuperscript{29} or as a way to generate an active species.\textsuperscript{30}

![Figure 3.1: Complexes that have been proposed to act as cooperative catalysts for different types of transformations via reversible cyclometalation by Mashima \textit{et al.}, Thiel \textit{et al.}, and Guan \textit{et al.}, respectively.](image)

Computational studies by Vanka \textit{et al.} indicate that reversible cyclometalation with Ir\textsuperscript{ill} could be useful for NH\textsubscript{3}BH\textsubscript{3} dehydrogenation and, furthermore, could also be a suitable mechanism for formic acid dehydrogenation to CO\textsubscript{2} and H\textsubscript{2}.\textsuperscript{28} Dihydrogen is considered a key component of many future renewable energy solutions, but efficient and reversible storage and release of H\textsubscript{2}, e.g. in organic liquids such as formic acid (FA), are essential for a hydrogen based economy. Most catalytic systems for the dehydrogenation of HCOOH to H\textsubscript{2} and CO\textsubscript{2} require the presence of exogenous base,\textsuperscript{31–33} which not only decreases the overall hydrogen content from 4.4 wt\% (for pure HCOOH) to 2.3 wt\% (for a typical 5:2 HCOOH/NEt\textsubscript{3} mixture) but also necessitates post-catalysis processing for fuel cell applications (removal of volatile amines).\textsuperscript{34–36} Hence, catalytic formic acid dehydrogenation should ideally be performed in the absence of such exogenous base, but to date only a handful of systems capable of base-free formic acid dehydrogenation have been reported.\textsuperscript{9,37–44} Given our interest in the design of reactive ligand systems for cooperative bond activation reactions and catalytic processes,\textsuperscript{45–52} we wondered whether reversible C-H activation in the coordination sphere of a metal could serve as a new methodology to facilitate e.g. formic acid dehydrogenation. In such a strategy, a metal-carbon fragment should function as an internal base for the activation of a suitable protic substrate. A hypothetical cooperative mechanism based on reversible cyclometalation as a bond-activation concept involves i) M-C bond assisted E-H bond activation, ii) productive conversion of the activated M-E moiety into a product-like M-Y fragment and iii) ligand-assisted Y-H bond reductive elimination (Figure 3.2). Reversible cyclometalation by protonation of the M-C bond might result in a weakly coordinating agostic C-H bond.\textsuperscript{53–54} This fragment could be viewed as masking a vacant site at the metal center, without significant perturbations (structural or electronic) of the global ligand framework, unlike what is often encountered for other reactive ligands. An agostic C-H interaction might also assist in stabilizing catalytically relevant intermediates, with beneficial implications for the overall energy profile of a potential reaction path.

In Chapter 2, the synthesis and reactivity of cyclometalated Rh\textsuperscript{i} complex 1 was described. The complex bears the deprotonated derivative of ligand L\textsuperscript{H} that can act either as a neutral bidentate PN-ligand or as anionic tridentate PNC-system, depending on the
reaction conditions. Based on these initial results, we speculated that the ligand-based reactive carbon center in the coordination sphere of Rh\textsuperscript{I} could be employed as bifunctional motif in metal-ligand cooperativity. In this chapter we investigate the reactivity of the Rh-C\textsubscript{Ar} bond in cyclometalated PNC-complexes with substrates containing E-H bonds and report the use of complex 1 as catalyst for the dehydrogenation of formic acid using reversible cyclometalation as cooperative motif.

### 3.2 Results and discussion

#### 3.2.1 Reactivity of 1 with weak protic donors

The cyclometalated complex 1 was shown to be susceptible to Rh-C cleavage by ethereal HBF\textsubscript{4} as strong acid in chapter 2. This generates a Rh\textsuperscript{I} complex with an agostic Rh-(C\textsubscript{Ph}-H) bond in the solid state, possibly via protonation of the metal to create a Rh\textsuperscript{II}(hydride) intermediate, with subsequent C-H reductive elimination. Furthermore, facile methylation at the cyclometalated carbon results from reaction of 1 with MeI. Based on these initial results, the activation of less reactive substrates was investigated. Initial attempts to activate alcohols or phenylacetylene at r.t. did not result in Rh-C cleavage, based on NMR spectroscopy. This may point toward either a \( pK_a \) mismatch between these protic substrates and the metal-carbon bond as 'internal base' or to unfavorable steric interference that prevents formal oxidative addition at the metal center.

Scheme 3.1: Reactivity of Rh\textsuperscript{I} complex 1 in the presence of 1,3-propanedithiol and trifluoromethanesulfonamide.
Aliphatic thiols did react smoothly with 1, judging from the rapid color change of the solution from red to light-yellow (Scheme 3.1). In line with this, the $^{31}$P NMR spectrum shows a doublet at $\delta$ 76.31 ppm ($J_{\text{RhP}} = 101$ Hz) for 1, while the reaction with 1,3-propanedithiol led to a doublet at $\delta$ 69.75 ppm ($J_{\text{RhP}} = 151.7$ Hz) for complex 2. A strong IR-band for the carbonyl was present at $\nu$ 1938 cm$^{-1}$ ($\Delta \nu$ of 5 cm$^{-1}$ vs 1), while the pyridine signals were significantly shifted downfield in the $^1$H NMR spectrum. These data suggest decoordination of the pyridine donor and thus monodentate P-coordination of the PNCH framework, induced by the tendency of thiolate fragments to bridge to metal centers. This hypothesis was corroborated by X-ray crystal structure determination on single crystals of 2 grown from a concentrated acetone-$d_6$ solution (Figure 3.3). The geometry around each Rh$^1$-center is square planar and the overall structural features with the gem-dithiolate core resemble those reported in literature.55–57

Figure 3.3: ORTEP (ellipsoids set at 50% probability) for complex 2. Selected bond lengths [Å] and angles [°]: Rh1-P1 2.3163(5); Rh1-C211 1.827(2); Rh1-S13 2.3940(5); Rh1-S23 2.3784(5); Rh2-P2 2.3154(6); Rh1-C212 1.808(2); Rh2-S13 2.3833(5); Rh2-S23 2.3948(5); Rh1âRh2 3.0845(2); P1-Rh1-S13 94.682(18); S13-Rh1-S23 82.762(18); P2-Rh2-S23 93.690(19); S13-Rh2-S23 82.642(18). Angle sums Rh1: 359.99(10); Rh2: 360.44(12) °. Dihedral angle between S-Rh-S planes: 61.27(3)°.

Similar spectroscopic observations were made when reacting 1 with benzyl mercaptan. Notably, the reaction of 1 with thiophenol gave different spectral features, with a doublet at $\delta$ 99 ppm ($J_{\text{RhP}} = 136$ Hz) in MeCN-$d_3$. When C$_6$D$_6$ was used as a solvent, two species with similar shifts and coupling constants as complex 2 were observed, i.e. doublets at $\delta$ 66 ppm ($J_{\text{RhP}} = 152$ Hz) and $\delta$ 72 ppm ($J_{\text{RhP}} = 152$ Hz). The species interconvert when the solvent is changed within the same sample. These results could be an indication that monomeric complexes are formed when polar solvents are used in the reaction, but no conclusive evidence, such as a crystal structure or mass analysis, could be obtained. Because of the decoordination of the pyridine from the metal, we did not pursue catalytic (hydroaddition) transformations involving thiols, as the proposed cooperative nature of reversible cyclometalation requires close proximity of the
C-H bond to the metal mediated by the directing force of the pyridine group.

Trifluoromethylsulfonamide also reacts rapidly with the Rh-C bond, as evidenced by a $^{31}$P shift for the resulting amide complex 3 at δ 103.7 ppm ($J_{\text{RhP}} = 152$ Hz) (Scheme 3.1). The combined spectroscopic data are similar to previously reported Pd(CH$_3$)(RPN)(triflamide) species so a similar geometry, with the triflamide trans to phosphorus, is proposed, although single crystalline material could not be obtained for this compound. Unfortunately, complex 1 did not react with less acidic amines and therefore we also did not pursue catalytic activity based on these type of substrates. The installment of substituents on the phenyl ring could increase the reactivity, as they may influence the strength of the Rh-C bond, but the synthesis of these adapted ligands is more cumbersome.

3.2.2 DFT calculations on H$_2$ activation with 1

Next to exploring the stoichiometric reactivity of the M-C with protic substrates, we sought to apply the concept of reversible cyclometalation in cooperative catalysis. Typical reactions in which cooperative catalysts are commonly applied with outstanding results are hydrogenation and dehydrogenation reactions of polar substrates. Hydrogenation reactions can follow mechanisms in which metal-ligand bifunctional heterolytic H$_2$ activation is a crucial step. Unfortunately, species 1 appeared stable under an H$_2$ atmosphere (20 bar) at RT, indicating a relatively high barrier for heterolytic cleavage of H$_2$ to generate putative species A, Rh(H)(CO)(1$^\text{H}$). Increasing the H$_2$-pressure to 35 bar and heating an NMR sample for 1 hour at 70 °C also did not result in any observable hydride species. This ‘inertness’ to heterolytic H$_2$ activation could also mean that, instead of a high transition state barrier, the cyclometalated species is just more stable than intermediate A. If this is the case, H$_2$ evolution from A to generate 1 is energetically favourable. To obtain more insight in the energy landscape between A and 1, we performed DFT calculations (BP86, def2-TZVP, disp3 corrections) on monohydride complex A (Figure 3.4). This species may convert, via agostic intermediate B and subsequent C$_\text{Ph}$-H oxidative addition, to dihydride C with a low barrier of 7.2 kcal mol$^{-1}$. This dihydride subsequently undergoes smooth reductive elimination of H$_2$ (6.9 kcal mol$^{-1}$ barrier) to generate 1 as stable product ($\Delta G = -7.6$ kcal mol$^{-1}$). As a result, this cyclometalated complex may thus be a catalytically competent species for dehydrogenation reactions, which involve H$_2$ production.
3.2.3 Catalytic dehydrogenation of formic acid

To capitalize on the apparent facile loss of H\textsubscript{2} from putative species A in combination with the potential reactivity of the metal-carbon bond in metal-ligand bifunctional dehydrogenative catalysis and to illustrate the concept of reversible metalation for cooperative bond activation, we studied the dehydrogenation of formic acid as proof-of-principle reaction. Addition of 20 molar equiv HCOOH to 1 in MeCN instantaneously resulted in a yellow complex that can be characterized as formate derivative 4 (Scheme 3.2). Complex 4 (\textsuperscript{31}P: \delta 105 ppm, J\textsubscript{RhP} 167 Hz) is the only species present at r.t., but upon warming to 55 °C in a closed NMR tube, deep-red species 1 is regenerated within 45 minutes. No trace of remaining HCOOH was observed, and the formation of H\textsubscript{2} was detected (Figure 3.5).

Use of HCOOD resulted in selective deuteration of both ortho-C-H groups on the phenyl ring in 1, which is in line with cooperative activation of FA over the Rh-C bond. Smooth catalytic dehydrogenation of HCOOH was established using 0.5 mol% of species 1 in dioxane at 75 °C, with a turnover frequency (TOF) of 169 mol·mol\textsuperscript{-1}·h\textsuperscript{-1} (see Figure 3.6 and Table 3.1). The conversion was determined by gas collection with a water-displacement set-up and the TOF was determined around 20% conversion.
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Figure 3.5: Catalytic reaction (0.02 mmol cat. 1, 0.4 mmol HCOOH, 2 mL MeCN, 55 °C → 60 °C) in 10mm HP-NMR tube, monitored by \textsuperscript{1}H NMR (left) and \textsuperscript{31}P NMR (right) over a time span of 45 min. NMR spectra are stacked under an angle of 15°.

Figure 3.6: Plot of the formation of H\textsubscript{2} and CO\textsubscript{2} in the HCOOH dehydrogenation reaction catalyzed by 1. Control experiments with complexes 5, 6 and 7 under various conditions are also depicted.

Addition of external base (NEt\textsubscript{3}) did not affect the catalytic activity, as the rate of the reaction was not faster when the azeotrope HCOOH/NEt\textsubscript{3} = 5:2 is used. However, when using NEt\textsubscript{3}, the TOF can be increased by adding more HCOOH (at the same concentration of catalyst). In contrast, increasing the concentration of HCOOH in the absence of a base results in loss of activity, possibly because a dormant species is formed by overprotonation of complex 1, i.e. reaction of 1 with 2 equiv. of HCOOH. In CDCl\textsubscript{3} and CD\textsubscript{2}Cl\textsubscript{2} the formation of a new Rh-species is observed in NMR (δ = 112 ppm, \textsuperscript{1}J\textsubscript{RhP} = 182 Hz) and IR (2012 cm\textsuperscript{-1}) at high concentration of HCOOH, which supports the formation of this inactive species. However, in the solvents used for catalysis, MeCN and dioxane, this new species could not be identified as only some broadening of the NMR signals is observed at high concentration of HCOOH. This impedes the characterization of a
tentative dormant species.

Table 3.1: Catalytic activity in HCOOH dehydrogenation for studied complexes.ª

<table>
<thead>
<tr>
<th>Entry</th>
<th>Catalyst</th>
<th>Additive</th>
<th>TOF (h⁻¹)b</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Complex 1</td>
<td>-</td>
<td>169 ± 12</td>
</tr>
<tr>
<td>2</td>
<td>Complex 1</td>
<td>NEt₃</td>
<td>155 ± 20</td>
</tr>
<tr>
<td>3</td>
<td>Complex 5</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>Complex 5</td>
<td>1 equiv KOTBu</td>
<td>112 ± 4</td>
</tr>
<tr>
<td>5</td>
<td>Complex 6</td>
<td>-</td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td>Complex 7</td>
<td>-</td>
<td>0</td>
</tr>
</tbody>
</table>

ª Catalyst (0.01 mmol), HCOOH (2 mmol), (NEt₃ (0.8 mmol)), dioxane (1 ml), 75 °C. Experiments are performed at least in duplo.

b TOFs were determined from the slope of the curve around 20% conversion.

Figure 3.7: (a) Plot of the formation of H₂ and CO₂ from HCOOH catalyzed by complex 1 with intermittent addition of formic acid. Every time, around 65% conversion (indicated by the arrows), 1.3 mmol of extra HCOOH is added. The inset shows an overlay of the consecutive cycles. Only after the 7th cycle, some loss in activity is observed. (b) Similar plot for a catalytic experiment with complex 5 after activation with KOTBu.

Catalyst 1 showed reproducible performance during eight consecutive runs (total TON of 1024, Figure 3.7(a)). Only in the last cycle, some loss in activity is observed. The gaseous fraction produced during reaction was analyzed by GC and no CO was found within the detection limit (δ = 10 ppm). Although the TOF achieved is still moderate under these (unoptimized) conditions, this represents the first example of base-free formic acid dehydrogenation using a Rh¹ complex.⁵⁹,⁶⁰

To get more insight in the Rh-species present under catalytic conditions, in situ IR experiments were performed. The CO-group on the active Rh-species gives a nice handle to follow catalytic experiments. Moreover, the potential formation of detrimental Rh-COₓ species can be monitored. Unfortunately, the results in dioxane were not
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conclusive because the solvent residual signals were overlapping with the Rh-CO signals. In THF, however, the reaction could be monitored, showing that the only two species present under catalytic conditions are complexes 1 and 4, as indicated by the signals at 1945 cm$^{-1}$ and 1988 cm$^{-1}$, respectively (Figure 3.8). The experiment also shows that the concentration CO$_2$ (2330 cm$^{-1}$) increases over time and the concentration HCOOH decreases (1730 cm$^{-1}$).

Figure 3.8: (a) Zoom of the IR spectrum between 1600 and 2400 cm$^{-1}$ from the catalytic reaction in dioxane over a time span of 4.5 h. The red spectrum is recorded at the start and the blue after 4.5 h. The top spectrum is the residual spectrum of dioxane. (b) Zoom of the IR spectrum between 1600 and 2500 cm$^{-1}$ from the catalytic reaction in THF over a time span of 5 h. The red spectrum is recorded at the start and the blue after 5 h. The two Rh-CO peaks present can be attributed to complex 1 (1945 cm$^{-1}$) and complex 4 (1989 cm$^{-1}$). The concentration of complex 4 slowly decreases as it is converted back to complex 1.

To further confirm that no free CO or Rh-CO$_x$ species are formed, a catalytic reaction with H$^{13}$COOH was followed by $^{13}$C NMR (Figure 3.9). This experiment confirms that no new Rh-$^{13}$CO species are formed. Besides that, $^{31}$P NMR shows that complex 1 is selectively regenerated after catalysis.

Control experiments using complex 5 ([Rh(Cl)(CO)(PNH)]) bearing a bidentate PNH ligand (Figure 3.10) lacking the flanking phenyl arm, show very low conversion in absence of base, likely due to blocking of the fourth coordination site by the chloride ligand. Upon addition of one equivalent of strong base to deprotonate the PNH ligand and abstract the chloride ligand to form a vacant site, the system shows a similar TOF as complex 1. However, a different reaction profile is obtained, where the rate becomes faster at the end of the reaction, suggesting a different catalytic pathway for this catalyst compared to complex 1 (Figure 3.6). This catalyst is also stable for more than six hours with intermittent addition of HCOOH (Figure 3.7(b)). For every cycle, the same reaction profile is obtained which show that the catalyst is slower right after addition of HCOOH, ruling out that an incubation period is present to form the active catalyst. We expect that the deprotonation with a base leads to ligand ‘dearomatization’, as obtained product is darkly colored before addition of HCOOH.

\footnote{This behaviour is uncommon and suggests substrate inhibition takes place. Possibly, also this catalyst}
Figure 3.9: $^{13}$C NMR spectra of a catalytic dehydrogenation reaction with 1 and 200 equiv. of H$^{13}$COOH in dioxane at 75 °C followed over a time span of 2.5 hours in an open NMR tube. The experiment shows that no new Rh-CO species are formed under catalytic conditions. Spectra are stacked under an angle of 20 °.

Figure 3.10: Other Rh$^I$ complexes that were studied in the dehydrogenation of formic acid.

The same color is obtained when all the HCOOH has been decomposed to CO$_2$ and H$_2$. However, this does not necessarily mean that the dearomatized species is formed during catalytic turnover and it is not an explanation for the observed reaction profile. The known Rh$^I$-pincer complexes [Rh(CO)(PNN*)] (6)$^{62}$ and [Rh(CO)(PCP)] (7)$^{63}$ (PNN* = 6-di(tert-butyl)phosphinomethine-2,2'-bipyridine; see Figure 3.6) barely gave activity, suggesting that low-coordinate geometries and the presence of a ligand with adaptable denticity are important.

3.2.4 Mechanistic considerations

Based on these catalytic results, supported by DFT calculations, two catalytic cycles are conceivable [Scheme 3.3]. The first ‘intramolecular’ path involves reversible cyclometalation as key element. Cooperative activation of formic acid over the reactive Rh-C fragment to form formate species 4 proceeds with a moderate barrier of 17.4 kcal mol$^{-1}$. The transition state for a concerted hydride-proton-transfer step$^{64}$ could not be found, most likely because the hydride would be located in an unfavourable axial position (filled d$_{z^2}$ orbital) at Rh. Alternatively, HCOOH could also oxidatively add to form a Rh$^{III}$ intermediate that can undergo C-H bond formation via reductive elimina-
his vulnerable for ‘overprotonation’ with HCOOH forming a less active Rh$^{III}$ species. For complex 1 this phenomenon is observed as well, but leads to an inactive catalyst and more HCOOH is required to reach this state. The difference between the two complexes could be due to the relative basicity of the metal center.
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This option could not be ruled out by DFT calculations, as charged species cannot be compared to neutral species in gas phase calculations [Figure 3.11]. The same holds for protonation of 1 by HCOOH followed by immediate reductive elimination and coordination of the counterion, even though the reductive elimination of the protonated complex is almost barrierless [Figure 3.12].

\[
\begin{align*}
&\text{N} \quad \text{P} \quad (\text{tBu})_2 \quad \text{Rh} \quad \text{OC} \\
&\text{HCOOH} \\
&\text{N} \quad \text{P} \quad (\text{tBu})_2 \quad \text{Rh} \quad \text{OC} \\
&\text{O} \quad \text{O} \\
&\text{H} \quad \text{H} \quad \text{O} \\
&\text{N} \quad \text{P} \quad (\text{tBu})_2 \quad \text{Rh} \quad \text{OC} \\
&\text{H} \quad \text{H} \\
&\text{B} \\
&\text{N} \quad \text{P} \quad (\text{tBu})_2 \quad \text{Rh} \quad \text{OC} \\
&\text{H} \quad \text{H} \\
&\text{A} \\
&\text{N} \quad \text{P} \quad (\text{tBu})_2 \quad \text{Rh} \quad \text{OC} \\
&\text{H} \quad \text{H} \\
&\text{D} \\
&\text{H} \quad \text{H} \\
&\text{2} \\
&\text{HCOOH} \\
&\text{Bifunctional} \\
&\text{path} \\
&\text{Alternative} \\
&\text{Path} \\
&\text{r.d.s.} \\
&\text{Resting state} \\
&\text{4}, which lies -1.9 kcal mol\textsuperscript{-1} lower in energy than 1, converts to mono-hydride A via rate-limiting $\beta$-H elimination (18.2 kcal mol\textsuperscript{-1} relative to 4) concomitant with CO\textsubscript{2} release. Subsequent C-H oxidative addition via the Rh\textsuperscript{I}(C-H) agostic species B (a close analogue of a previously isolated cationic derivative, see chapter 2) and facile release of H\textsubscript{2} from Rh\textsuperscript{III} intermediate C regenerates 1 as the active catalyst (see Figure 3.4 for DFT profile from A to 1).

A second, non-cooperative path has very similar reaction barriers and shares the same rate-limiting step (from 4 to A), followed by oxidative addition of a second molecule of HCOOH to form dihydride intermediate D, which lies 0.8 kcal mol\textsuperscript{-1} higher in energy than A. Dihydride D generates H\textsubscript{2} via reductive elimination with a TS barrier of 5.3 kcal mol\textsuperscript{-1} [Figure 3.13]. Given the near-identical overall reaction profiles (with a shared rate limiting step with a barrier of ca. 18 kcal mol\textsuperscript{-1}), both mechanisms likely are catalytically competent and thus co-exist under catalytic conditions, regenerating species 1 during and/or after catalysis. The involvement of the cooperative path is supported by selective deuteration experiments, isolation of an agostic C-H model complex as a relevant intermediate, the regeneration of 1 with conversion of HCOOH and release of H\textsubscript{2} in NMR experiments.

Scheme 3.3: Proposed mechanisms for the base-free cooperative dehydrogenation of formic acid using 1 as catalyst. The DFT calculated values for the relative transition state barriers are shown in kcal mol\textsuperscript{-1}.

Resting state 4, which lies -1.9 kcal mol\textsuperscript{-1} lower in energy than 1, converts to mono-hydride A via rate-limiting $\beta$-H elimination (18.2 kcal mol\textsuperscript{-1} relative to 4) concomitant with CO\textsubscript{2} release. Subsequent C-H oxidative addition via the Rh\textsuperscript{I}(C-H) agostic species B (a close analogue of a previously isolated cationic derivative, see chapter 2) and facile release of H\textsubscript{2} from Rh\textsuperscript{III} intermediate C regenerates 1 as the active catalyst (see Figure 3.4 for DFT profile from A to 1).

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Figure 3.11: DFT (BP86, def2-TZVP, disp3) calculated free energy surfaces ($\Delta G^{0}_{298K}$ in kcal mol$^{-1}$) of the reaction of HCOOH with complex 1. This reaction can either occur through direct protonation of the Rh-C bond or through oxidative addition of HCOOH to form a Rh$^{III}$ intermediate. From these results it can be ruled out that protonation occurs via cis oxidative addition because the TS-barriers are too high. The pathway from the trans Rh$^{III}$ intermediate has low-lying TS-barriers (lower than direct protonation) but the TS for oxidative addition (?) could not be located because the energy of charged species is highly overestimated in gas phase calculations.

Figure 3.12: DFT (BP86, def2-TZVP, disp3) calculated free energy surface ($\Delta G^{0}_{298K}$ in kcal mol$^{-1}$) of the direct protonation of complex 1 by HCOOH followed by C-H reductive elimination.
3.3 Conclusion

In this Chapter we investigated whether reversible cyclometalation may be successfully employed as motif for cooperative bond activation processes. As a start, it was shown that complex 1 readily reacts with thiols and acidic amines, which leads to protonation of the anionic carbon of the reactive flexidentate ligand L. Unfortunately, complex 1 does not react with less activated substrates such as H₂ but DFT calculations show that, instead, release of dihydrogen is facile from a putative monohydride complex A. This suggests that complex 1 might be a competent catalyst for dehydrogenation reactions.

Reaction of cyclometalated complex 1 with a small excess of formic acid results in formate adduct 4. Under catalytic conditions, base-free formic acid dehydrogenation could be successfully established with Rh¹ complex 1. Although the TOF (169 h⁻¹) is not as high as for several other catalysts based on e.g. Ru or Ir, this is the first example of base-free HCOOH dehydrogenation with Rh¹. Detailed NMR and IR experiments point out that the only Rh-CO species present under catalytic conditions are complex 1 and complex 4. Regeneration of 1 after catalysis was also supported by NMR spectroscopy.

From a comparison of the catalytic activity of complex 1 to complexes 6 and 7, which show almost no activity, it is clear that the flexidentate character of the phenyl group in complex 1 is beneficial compared to more rigid systems. On the other hand, similar activities are found for complex 1 and complex 5 (activated with 1 equiv of KOtBu), suggesting that the phenyl-group may not be required. However, the difference in the

Figure 3.13: DFT (BP86, def2-TZVP, disp3) calculated free energy profile (ΔG²⁹⁸K in kcal mol⁻¹) of the dehydrogenation of HCOOH following a non-cooperative pathway.
shape of the catalytic curves for 1 and 5 point out that, most likely, the operating mechanisms are different for these two catalysts. Experimental observations in combination with DFT studies support that a cooperative mode of action based on reversible cyclometalation could be a feasible mechanism for this reaction. However, definitive proof for the reversible cyclometalation mechanism could not be obtained due to a competing non-cooperative pathway that has the same r.d.s. and similar overall barriers. Most likely, both mechanisms co-exist under catalytic conditions. Furthermore, for HCOOH dehydrogenation, this mode of cooperativity did not result in the anticipated benefits, in terms of TOF, over traditional systems (and other cooperative systems) because the r.d.s., CO$_2$ release from the formate species, is not a bifunctional step. On the positive side, complex 1 turned out to be a rather stable catalyst, showing reduced activity only after the seventh consecutive cycle.

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### 3.4 Experimental section

**General methods.** All reactions were carried out under an atmosphere of nitrogen using standard Schlenk techniques. Reagents were purchased from commercial suppliers and used without further purification. THF, pentane, hexane and Et$_2$O were distilled from sodium benzophenone ketyl. CH$_2$Cl$_2$ was distilled from CaH$_2$, toluene from sodium under nitrogen. NMR spectra ($^1$H, $^13$C, $^31$P, $^31$P-H and $^{13}$C-H) were measured on a Bruker DRX 500, Bruker AV 400, Bruker DRX 300 or on a Bruker AV 300 spectrometer. IR spectra (ATR mode) were recorded with a Bruker Alpha-p FT-IR spectrometer. High resolution mass spectra were recorded on a JMS-T100GCV mass spectrometer using field desorption (FD).

**Synthesis of Rh$_2$(SCH$_2$CH$_2$CH$_2$S)(CO)$_2$(κ$_1$-P-1H)$_2$ (2).** To a solution of 1 (10 mg, 23 µmol) in CH$_2$Cl$_2$ (1 mL) was added 1,3-propanedithiol (1.1 µL, 23 µmol), resulting in an immediate color change from red to dark yellow. The solvent was evaporated to yield 2 in quantitative yield (11 mg). $^1$H NMR (300 MHz, 298 K, CD$_2$Cl$_2$, ppm): δ 8.44 (d, J = 6.3 Hz, 2H), 8.14-8.07 (m, 4H), 7.63-7.40 (m, 10H), 4.21-3.82 (m, 4H), 2.95-2.69 (m, 4H), 2.42-2.30 (m, 2H), 1.53 (d, J = 12.7 Hz, 18H), 1.41 (d, J = 12.9 Hz, 18H). $^{31}$P NMR (121 MHz, 298 K, CD$_2$Cl$_2$, ppm): δ 69.75 (d, J = 151.7 Hz). $^{13}$C NMR (75 MHz, 298 K, CD$_2$Cl$_2$, ppm): δ 190.58 (dd, J$_{RhC}$ = 73.4 Hz, J$_{CP}$ = 14.9 Hz, CO), 157.28 (s, Py-C), 155.81 (s, Py-C), 139.48 (s, Py-CH), 136.22 (s, Py-CH), 128.71 (s, Ph-CH), 128.58 (s, 2C, Ph-CH), 126.75 (s, 2C, Ph-CH), 124.71 (d, J = 2.8 Hz, Py-CH), 117.89 (s, Py-CH), 38.67 (s, SCH$_2$CH$_2$), 37.31 (d, J = 16.2 Hz, PC(CH$_3$)$_3$), 36.93 (dd, J = 15.7, 1.3 Hz, CH$_2$P), 31.71 (d, J = 13.0 Hz, SCH$_2$CH$_2$), 30.16 (dd, J = 17.4, 3.8 Hz, PC(CH$_3$)$_3$). IR (ATR, cm$^{-1}$): ν CO 1938. HRMS (FD): m/z calcd for C$_{44}$H$_{62}$N$_2$O$_2$P$_2$Rh$_2$S$_2$: 966.18888 [M-CO]$^+$; found: 966.18386.
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Synthesis of Rh(NHSO\textsubscript{2}CF\textsubscript{3})(CO)(\kappa\textsuperscript{2}-P,N-\textit{t}\textit{Bu}) (3). To a solution of 1 (12 mg, 27 \textmu mol) in CH\textsubscript{2}Cl\textsubscript{2} (1 mL) was added trifluoromethylsulfonamide (4 mg, 27 \textmu mol), resulting in a color change from red to yellow in quantitative yield (16 mg). \textit{H} NMR (300 MHz, 298 K, CD\textsubscript{2}Cl\textsubscript{2}, ppm): \delta 8.20-8.12 (m, 2H, Ph), 7.90 (t, \textit{J} = 7.8 Hz, 1H, Py), 7.68-7.59 (m, 3H, Ph), 7.52 (t, \textit{J} = 8.3 Hz, 2H, Py), 3.75 (d, \textit{J} = 9.3 Hz, 2H, CH\textsubscript{2}P), 1.41 (d, \textit{J} = 14.1 Hz, 18H, PtBu\textsubscript{2}), 1.14 (s, 1H, NH). \textit{C} NMR (75 MHz, 298 K, CD\textsubscript{2}Cl\textsubscript{2}, ppm): \delta 192.98 (s, Py-C), 161.96 (s, Py-C), 161.86 (d, \textit{J}_{CP} = 166.8 Hz). IR (ATR, cm\textsuperscript{-1}): \nu CO 1973. HRMS (FD): \textit{m}/\textit{z} calcd for C\textsubscript{22}H\textsubscript{30}F\textsubscript{3}N\textsubscript{2}O\textsubscript{3}PRh\textsubscript{S}: 593.0721 [M]+; found: 593.0721.

Synthesis of Rh(OCH(O)(CO)(\kappa\textsuperscript{2}-P,N-\textit{t}\textit{Bu}) (4). To a solution of 1 (4.4 mg, 10 \textmu mol) in CD\textsubscript{3}C\textsubscript{2} (0.6 mL) was added formic acid (9.2 mg, 200 \textmu mol), resulting in an immediate color change from red to yellow at room temperature. Due to its unstable nature, this species was only characterized in situ using NMR spectroscopy. \textit{H} NMR (400 MHz, 298 K, CD\textsubscript{3}C\textsubscript{2}, ppm): \delta 8.01-7.94 (m, 2H, Ph), 7.90 (t, \textit{J} = 7.7 Hz, 1H, Py), 7.57-7.39 (m, 5H, 2Py, m-Ph, p-Ph), 3.73 (d, \textit{J}_{PH} = 9.6 Hz, 2H), 1.38 (d, \textit{J}_{PH} = 14.3 Hz, 18H). \textit{C} NMR (121 MHz, 298 K, CD\textsubscript{2}Cl\textsubscript{2}, ppm): \delta 105.29 (d, \textit{J}_{RHC} = 166.8 Hz).

Synthesis of Rh(Cl)(CO)(\kappa\textsuperscript{2}-PN-2-methyl-6-((di-\textit{tert}-butylphosphino)methyl)-pyridine) (5). To a solution of 2-methyl-6-((di-\textit{tert}-butylphosphino)methyl)-pyridine (0.025 g, 10 \textmu mol) in CH\textsubscript{2}Cl\textsubscript{2} (0.5 mL) was added a solution of [Rh(CO)\textsubscript{2}(\mu-Cl)]\textsubscript{2} (0.019 g, 5 \textmu mol) in CH\textsubscript{2}Cl\textsubscript{2} (2 mL) and the reaction mixture was stirred overnight. After evaporation of the solvent, the product was washed with pentane (1 mL), yielding the desired complex as yellow powder (0.038 g, 92 \textmu mol). \textit{H} NMR (300 MHz, 298 K, acetone-d\textsubscript{6}, ppm): \delta 7.77 (t, \textit{J} = 7.7 Hz, 1H, Py), 7.46 (d, \textit{J} = 7.7 Hz, 1H, Py), 7.26 (d, \textit{J} = 7.7 Hz, 1H, Py), 3.93 (d, \textit{J}_{PPH} = 9.6 Hz, 2H, CH\textsubscript{2}P), 3.10 (s, 3H, Py-CH\textsubscript{3}), 1.32 (d, \textit{J}_{PPH} = 13.9 Hz, 18H, (CH\textsubscript{3})CP). \textit{P} NMR (121 MHz, 298 K, CD\textsubscript{2}Cl\textsubscript{2}, ppm): \delta 106.12 (d, \textit{J}_{RHP} = 165.0 Hz). \textit{C} NMR (75 MHz, 298 K, acetone-d\textsubscript{6}, ppm): \delta 191.85 (dd, \textit{J} = 73.4, 14.5 Hz, CO), 163.78 (s, Py-C), 162.52 (d, \textit{J} = 3.9 Hz, Py-C), 139.74 (s, Py-CH\textsubscript{3}), 124.56 (Py-CH), 124.46 (d, \textit{J} = 9.0 Hz, Py-CH), 36.05 (d, \textit{J}_{CP} = 20.3, \textit{J}_{RHC} = 2.3 Hz, CH\textsubscript{2}P). IR (ATR, cm\textsuperscript{-1}): \nu CO 1958. HRMS(FD): \textit{m}/\textit{z} calcd C\textsubscript{26}H\textsubscript{26}Cl\textsubscript{19}OPRh: 417.04956 [M]+; found: 417.04984.

Standard catalytic experiment and control experiments. Typically, complex 1 (10 \textmu mol) was added to the solvent (1 mL) in a 5 mL Schlenk equipped with a condenser and connected to a water replacement setup. The reaction mixture was heated to required temperature and stirred for 10 minutes. Formic acid was added to the reaction mixture (75 \textmu L, 2 mmol) or the azeotrope HCOOH/NEt\textsubscript{3} 5:2 was added to the reaction mixture (187 \textmu L, 2 mmol HCOOH) and evolved gas was collected. In the case of complex Rh(Cl)(CO)(PN), first 1 equivalent of KtBu in THF (1M) was added at RT to abstract the chloride ligand. After 5 min stirring, 75 \textmu L HCOOH was added. The mixture was rapidly
heated to 75 °C and the evolved gas was collected. Evolved gases were analyzed with a G·A·S Compact GC (Rt-MSieve 5A 20 m × 0.32 mm + Rt-Q-bond 2 m × 0.32 mm). The amounts of mol converted were determined from the volumes of gas collected using equation 1.1 and 1.2.

\[ V_{H_2} = \frac{RT}{p} + b - \frac{a}{RT} = 24.99 \frac{L}{mol} \]  
\[ V_{CO_2} = \frac{RT}{p} + b - \frac{a}{RT} = 24.42 \frac{L}{mol} \]  

\[ R: 8.3145 \text{ m}^3 \cdot \text{Pa} \cdot \text{mol}^{-1} \cdot \text{K}^{-1} \]  
\[ T: 298.15 \text{ K} \]  
\[ p: 101325 \text{ Pa} \]  
\[ b: 26.7 \cdot 10^{-6} \text{ m}^3 \cdot \text{mol}^{-1} \]  
\[ a: 2.49 \cdot 10^{-10} \text{ Pa} \cdot \text{m}^3 \cdot \text{mol}^{-2} \]  

\[ R: 8.3145 \text{ m}^3 \cdot \text{Pa} \cdot \text{mol}^{-1} \cdot \text{K}^{-1} \]  
\[ T: 298.15 \text{ K} \]  
\[ p: 101325 \text{ Pa} \]  
\[ b: 42.7 \cdot 10^{-6} \text{ m}^3 \cdot \text{mol}^{-1} \]  
\[ a: 36.5 \cdot 10^{-10} \text{ Pa} \cdot \text{m}^3 \cdot \text{mol}^{-2} \]  

Catalytic experiment in MeCN followed by NMR. A 10 mm sapphire tube was charged with complex 1 (0.02 mmol), MeCN-d₃ (2 ml) and HCOOH (0.4 mmol, 20 equiv.). The tube was sealed and was heated to 60 °C. The reaction was followed for 45 min.

Catalytic experiment with H¹³COOH in dioxane followed by NMR. A 10 mm sapphire tube was charged with complex 1 (0.02 mmol), dioxane-d₈ (2 mL) and H¹³COOH (4 mmol, 200 equiv.). The tube was not completely sealed to prevent build-up of pressure. The tube was heated to 75 °C and the reaction was followed for 2.5 hours.

Catalytic experiment followed with IR. A catalytic experiment is followed by IR in an high pressure autoclave equipped with an IR cell. The autoclave is charged with dioxane or THF (6 mL) and pressurized with 2 bar of helium (in order to fill the IR cell) and heated to 75 °C (60 °C for THF). A blank spectrum is recorded. Then the pressure is slowly released and complex 1 (0.03 mmol) and HCOOH (6 mmol, 200 equiv.) dissolved in 1 mL dioxane (or THF) are added to the autoclave, after which it is again pressurized with 2 bar of helium.

X-ray crystal structure determination of complex 2. C₄₅H₆₂N₂O₂P₂RhS₂, \( M_r = 994.85 \), yellow block, 0.25 × 0.19 × 0.09 mm³, monoclinic, \( P2_1/n \) (no. 14), \( a = 12.7487(4) \), \( b = 19.7725(6) \), \( c = 18.4361(5) \) Å, \( \beta = 103.046(1) \) °, \( V = 4527.3(2) \) Å³, \( Z = 4 \), \( D_x = 1.460 \) g/cm³, \( \mu = 0.93 \) mm⁻¹. 60826 Reflections were measured on a Bruker Kappa ApexII diffractometer with sealed tube and Triumph monochromator (\( \lambda = 0.71073 \) Å) at a temperature of 150(2) K up to a resolution of \( (\sin \theta/\lambda)_{\text{max}} = 0.65 \) Å⁻¹. X-ray intensities were measured on a Bruker Kappa ApexII diffractometer with sealed tube and Triumph monochromator (\( \lambda = 0.71073 \) Å) at a temperature of 150(2) K. The intensities
were integrated with the Eval15 software. Multi-scan absorption correction and scaling was performed with SADABS (correction range 0.67-0.75). 10392 Reflections were unique (R_{int} = 0.039), of which 8330 were observed \([I > 2\sigma(I)]\). The structure was solved with Patterson superposition methods using SHELXT. Least-squares refinement was performed with SHELXL-97 against \(F^2\) of all reflections. Non-hydrogen atoms were refined freely with anisotropic displacement parameters. All hydrogen atoms were located in difference Fourier maps and refined with a riding model. 508 Parameters were refined with no restraints. \(R_1/wR_2\) \([I > 2\sigma(I)]\): 0.0255 / 0.0542. \(R_1/wR_2\) [all refl.]: 0.0396 / 0.0580. \(S = 1.023\). Residual electron density between -0.32 and 0.32 e/Å³. Geometry calculations and checking for higher symmetry was performed with the PLATON program. CCDC 1422009 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

DFT Calculations. Geometry optimizations were carried out with the Turbomole program package coupled to the PQS Baker optimizer via the BOpt package at the ri-DFT level using the BP86 functional and the resolution-of-identity (ri) method. We optimized the geometries of all stationary points at the def2-TZVP basis set level, using Grimme’s dispersion corrections (disp3 version) and a tight energy grid (m5). The identity of the transition states was confirmed by following the imaginary frequency in both directions (IRC). All minima (no imaginary frequencies) and transition states (one imaginary frequency) were characterized by calculating the Hessian matrix. ZPE and gas-phase thermal corrections (entropy and enthalpy, 298 K, 1 bar) from these analyses were calculated using standard thermodynamics.

References

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