Rhodium catalysed conversion of carbenes into ketenes and ketene imines using PNN pincer complexes

Tang, Z.; Mandal, S.; Paul, N.D.; Lutz, M.; Li, P.; van der Vlugt, J.I.; de Bruin, B.

DOI
10.1039/C5QO00287G

Publication date
2015

Document Version
Final published version

Published in
Organic Chemistry Frontiers

License
CC BY-NC

Citation for published version (APA):
Tang, Z., Mandal, S., Paul, N. D., Lutz, M., Li, P., van der Vlugt, J. I., & de Bruin, B. (2015). Rhodium catalysed conversion of carbenes into ketenes and ketene imines using PNN pincer complexes. Organic Chemistry Frontiers, 2(12), 1561-1577. https://doi.org/10.1039/C5QO00287G
Rhodium catalysed conversion of carbenes into ketenes and ketene imines using PNN pincer complexes†

Z. Tang,a S. Mandal,a N. D. Paul,a M. Lutz,b P. Li,a J. I. van der Vlugta and B. de Bruina,a

Ketene synthesis involving catalytic carbynylation of carbenes is an interesting alternative to traditional synthetic protocols, offering milder conditions to diversified products. Analogous catalytic ketene imine production from carbenes and isocyanides is also a promising reaction. However, both methods are underdeveloped. Rhodium carbonyl complexes B and E, based on (6-(phosphinomethyl)pyridin-2-yl)-methan-sec-amine type PNN ligand scaffolds, reveal good catalytic activities in ketene and ketene imine production using ethyl diazoacetate (EDA, 1) or sodium 2-benzyldiene-1-tosylhydrazin-1-ide (5) as the carbene precursors, as demonstrated by in situ amide/imidamide and β-lactam synthesis. DFT calculations suggest that diazo activation is the rate-determining step and that NH-deprotonation of the ligand produces a more active rhodium complex. The ketene formation step likely proceeds via an outer-sphere CO insertion mechanism. Subsequent stepwise and concerted [2 + 2] cyclization mechanisms have comparable barriers. The complexes are the first rhodium catalysts reported for catalytic ketene/ketene imine production from carbenoids. The higher affinity of rhodium for binding ketene or ketene imine intermediates as compared to other reported metal catalysts (i.e. Pd, Co) may provide opportunities for future enantioselective reactions when using chiral ligands.

Introduction

Ketenes are highly reactive and useful intermediates to a wide range of important chemicals for pharmaceuticals and fine chemicals, such as esters, amides, β-lactons or β-lactams. Ketene imines, the isoelectronic nitrogen analogues, are also reactive and versatile intermediates that tend to undergo analogous coupling reactions to give relevant nitrogen-containing compounds. Ketenes are conventionally synthesized by thermolysis, Wolff rearrangement or dehydrohalogenation of acyl halide precursors. These methods generally have limitations, such as a narrow substrate scope, strictly controlled conditions and generation of detrimental side products. Ketene imines are generally synthesized from ketenes via anaza-Wittig reaction, various rearrangement reactions or azide–alkyne coupling. These methods have similar limitations concerning the substrate scope and reaction conditions.

Carbynylation of carbenes to give ketene formation was reported in 1912, and the reactivity to undergo carbynylation has remained a characteristic feature of carbenes. A number of early or late transition metal complexes have been reported to mediate carbynylation of carbenes to form ketenes. Carbonylation chemistry has a close connection with carbenes, with carbynylation of carbenes being reported only very recently. Ketenes were generated with these catalysts in decent yields under generally mild conditions (1–20 bar of CO, 50–60 °C), and in situ converted for the synthesis of a range of esters, amides and β-lactams (Scheme 1), using diazo and N-tosylhydrazones compounds as carbene precursors.

Although stereocontrol in the coupling reactions of ketene is highly desirable, the transition metal catalysts reported thus far for ketene formation from carbene precursors are not...
able to promote the follow-up coupling reactions in an enantioselective or diastereoselective manner (e.g., when several chiral Co(porphyrin) complexes were used as catalysts, no ee was detected). This is attributed to a low affinity of the metal ions to bind the ketene intermediate, which as a result undergoes coupling reactions after its release from the metal centre.

A single molecular catalyst that can catalyse ketene formation from carbenes and can induce stereo- or diastereoselectivity in the coupling reactions would be highly desirable. Our consideration on catalyst development for this purpose was to utilize the Rh(PNN) scaffold developed earlier in our lab, as rhodium has been recognized as one of the most active metals to mediate the carbylation of carbenes to form ketenes, and rhodium should have a relatively high affinity to bind the ketene intermediates, of key-importance for future chirality transfer. In addition, the PNN ligand is a versatile scaffold with both the amine and the phosphine available to install chiral auxiliaries in future studies. The rigidity of the pincer ligand is also expected to provide stability to the metal complex during the reaction. Furthermore, derivatives of the complexes upon –NH deprotonation are accessible, offering easy modification and diversity in the number of complexes to screen for catalytic activity. While the studies in this report focus on achiral model systems, the results are nonetheless relevant for future development of enantioselective catalysis.

In the envisioned catalytic working model, the diazo compound (ethyl diazoacetate, EDA, is taken as an example in Scheme 1) first coordinates to Rh complex I before being converted to the metalcarbene intermediate II via N₂ loss. Subsequent CO insertion into the metalcarbene (via either an inner- or outer-sphere mechanism; the inner-sphere mechanism being shown in Scheme 1) then results in formation of the metal-ketene species III. Follow-up reactions, such as nucleophilic coupling or [2 + 2] imine-ketene cyclization, can occur in the coordination sphere of the metal. If the PNN ligand bears chiral substituents, enantioselective coupling may be envisioned. After the coupling, release of the product and (possible) coordination of exogenous CO would close the catalytic cycle. Ketene imines can be prepared in a similar manner by using isocyanides in place of CO. Examples of the stoichiometric reaction are not abundant, but examples of catalytic synthesis of ketene imines are even scarcer and limited to only two recently reported palladium catalysts. We therefore considered it worthwhile to develop a protocol for catalytic metal-mediated ketene imine synthesis, and these studies are included herein.

The main goals of the investigations presented here are: (I) To show that Rh(PNN) complexes are viable carbene-transfer catalysts for ketene and ketene imine synthesis, and (II) to investigate computationally whether the overall catalytic reaction could proceed via rhodium-coordinated ketenoid intermediates that undergo attack by external nucleophiles in the coordination sphere of rhodium (the latter being obviously relevant for future development of enantioselective strategies with chiral analogs of the complexes studied herein).

Results and discussion

Synthesis of the PNN ligands

The PNN ligands a and b, with phenyl substituents at phosphorus, were synthesized via pathway [1] (Scheme 2), a modifi-
cation from a previously reported procedure. Synthesis of a and b starts with condensation of 6-methylpicolinaldehyde with the desired amines, followed by imine reduction to the amines. The isolated amines were treated with two equivalents of n-butyl lithium (n-BuLi) in diethyl ether (Et2O) at −78 °C, with subsequent cannulation of this reaction mixture to a solution of Ph2PCl in Et2O at −78 °C and acidic work-up to afford the PNN ligands a and b in 15–20% overall yields.

The PNN ligands c–e, which bear alkyl substituents at phosphorus, were synthesized via pathway [2] (Scheme 3), also following a modified literature procedure. Borane was used as protecting group for the alkylphosphine intermediates to allow purification processes to be performed under aerobic conditions. Subsequent installation of the phosphine arm and the nitrogen arm on 2,6-bis(chloromethyl)pyridine followed by borane removal afforded the pincer ligands c, d and e in 34–44% overall yields.

**Synthesis of the PNN rhodium carbonyl complexes**

The targeted Rh(CO)(PNN) complexes were obtained by reaction of [Rh(CO)2(μ-Cl)]2 with two equivalents of the respective PNN ligands in methanol, followed by salt metathesis using NH4PF6 (Scheme 4). Five complexes were synthesized and isolated. Complexes A and B both have a phenyl-substituted phosphine arm, only differing in the substituent on the nitrogen arm (methyl for A and phenyl for B). Complexes C and D both have bulky 2,6-isopropylphenyl substituents on the nitrogen arm. They differ in the substituents at phosphorus atom (isopropyl for C and tert-butyl for D). Complex E is an analogue of complex D with a phenyl substituent on the nitrogen arm. Deprotonation of the amine moieties of cationic complexes B–E produces the neutral amido complexes B′–E′ (Scheme 4), but these were not isolated.

Yellow single crystals of complex A were obtained by storing a concentrated methanol solution of A at 0 °C, while crystalline material for B and E was obtained by top-layering the corresponding concentrated dichloromethane (DCM) solution with diethyl ether (Et2O). The X-ray crystal structures of the three complexes are depicted in Fig. 1, and selected bond lengths and angles are listed in Table 1. All the three complexes adopt a slightly distorted square planar geometry around Rh, with the plane defined by the atoms P1, N1 and N2. Bond lengths and angles around Rh in these complexes are similar. Slightly longer Rh–N2 bonds in B and E than in A (2.1609 and 2.1626(13) vs. 2.1381(10) Å) reflect a slightly weaker donor capacity of the N2 donor in complexes B and E. The infrared spectra in CD2Cl2 solution show a higher CO stretching frequency in B than in A (2007 vs. 2002 cm⁻¹) is in agreement with weaker metal-to-carbonyl back-donation in B. Lower CO stretching frequencies in complexes C, D and E were observed (1999, 1996 and 1999 cm⁻¹, respectively), as these ligands bear more electron-rich alkylphosphine ligands.

**Catalytic results**

Amide synthesis via catalytic ketene formation using EDA as the carbene precursor. The complexes A–E have been tested...
as catalyst precursors for catalytic ketene formation by carbonylation of carbenes (Table 2). Ethyl diazooacetate (EDA) was used as the carbene precursor, with toluene as the solvent at 60 °C under 20 bar of CO, and 4-nitro-aniline 2a was used as the nucleophile to trap the ketene intermediate. The reaction typically produced mixtures containing ethyl 3-((4-nitrophenyl)-amino)-3-oxopropanoate (3a) and ethyl (4-nitrophenyl)glycinate (4) (see Table 2), with 3a being the desired product resulting from the ketene intermediate II and 4 being an undesired side product from the direct reaction between 4-nitro-aniline 2a and carbene intermediate II (see also Scheme 1, for labeling of the intermediates II and III).

For complex A, poor selectivities with moderate or low yields to the desired amide product 3a were obtained, either in the absence or presence of K₂CO₃ (entries 1 and 2, Table 2). In contrast, the diphenylphosphine complex B with phenyl substituents on the amine nitrogen gave much better results in the presence of the base, both in terms of yield and selectivity to 3a (entries 4, 5, the small selectivity difference might originate from overlap of signals used for integration in the ¹H NMR spectra), while amine 4 was obtained as the major product in the absence of the base.

The nucleophilic coupling with the ketene appears to be accelerated to a larger extent than the side reaction under these basic conditions. This suggests that amine deprotonation of B to form the neutral amido complex B′ (see Scheme 4) is beneficial for the selectivity.

One might hypothesize that for the neutral amido complex B′ the carbene intermediate II is less prone to external attack by the aniline 2a, due to increased π-back donation to the carbene p-orbital (as a result of increased electron density) as compared to the cationic amine complex B, whereas CO migration or external CO attack to the carbene moiety to form the ketene might be facilitated by the increased nucleophilicity of the carbene ligand (taking advantage of the electron-accepting properties of CO). Control experiments showed that complex A was inert toward deprotonation by K₂CO₃, while B was readily deprotonated by K₂CO₃ in THF,24 consistent with the assumption that a neutral amido intermediate is the active species.

The poor performance of complexes C and D is probably related to steric shielding by the bulky side-groups in these ligands, while the less bulky complex E (in its deprotonated form E′) gave almost full conversion and a very high selectivity (3a/4 ratio >50) to 3a (entry 8) in 16 hours. Deprotonated complex E′ clearly outperforms all other catalysts screened in

---

**Table 1** Selected bond lengths (Å) and angles (°) for complex A,B and E

|     | A             | B             | E             |
|-----|---------------|---------------|---------------|
| Rh1-P1 | 2.2234(3)    | 2.2120(9)     | 2.2126(4)     |
| Rh1-N1 | 2.0540(9)    | 2.053(3)      | 2.0483(12)    |
| Rh1-N2 | 2.1381(10)   | 2.160(3)      | 2.1624(13)    |
| Rh1-C20 | 1.8283(12)  | 1.831(4)      | 1.8383(16)    |
| C20-O1 | 1.1489(15)   | 1.147(5)      | 1.139(2)      |
| P1-Rh1-N1 | 82.83(2)   | 83.59(8)      | 84.77(3)      |
| P1-Rh1-N2 | 161.78(3)  | 163.53(9)     | 161.18(4)     |
| N1-Rh1-C20 | 175.27(4)  | 175.19(15)    | 176.44(6)     |
| Rh1-C20-O1 | 178.01(12) | 176.0(4)      | 176.84(17)    |

---

**Table 2** Amide synthesis via in situ generated ketene with EDA as the carbene precursor

| Entry | Catalyst | 2 eq. K₂CO₃ | 3a + 4 yield (%) | 3a/4 ratio | Remarks |
|-------|----------|-------------|-----------------|-----------|---------|
| 1     | A        | ×           | 50              | 0.4       |         |
| 2     | A        | √           | 26              | 0.2       |         |
| 3     | B        | √           | 100             | 0.4       | 38 h    |
| 4     | B        | √           | 100             | 7.4       | 38 h    |
| 5     | B        | √           | 94              | 9.7       |         |
| 6     | C        | √           | 12              | 0.6       |         |
| 7     | D        | √           | 14              | 0.4       |         |
| 8     | E        | √           | 100             | >50       |         |
this study, both in terms of activity and selectivity. Complexes B’ and (in particular) E’ are thus determined to be supreme catalysts for ketene generation with EDA as the substrate.

Sodium N-tosyl hydrazone salt 5 as the carbene precursor. Interestingly, the product selectivity with respect to ketene formation versus direct attack of the carbenoid intermediate by the aniline substrate not only depends on the applied catalyst, but also on the carbene precursor used. With carbene precursor 5 (see Scheme 5) the selectivity of catalyst B’ can actually exceed that of E’. When using N-tosyldihydrozone salt 5 (sodium 2-benzylidine-1-tosylpyrazoline-1-ide), a precursor of [diazo- methyl]benzene, different catalytic activities and selectivities for the formation of amide product 6a were obtained, affording both a higher yield and selectivity with complex B’ as compared to E’. Interestingly, for these reactions an imine side product 7a was obtained instead of an amine product (Table 2). Formation of this imine side product 7a was confirmed by mass spectrometry and 1H NMR spectroscopy. This compound could well be formed in a condensation reaction of 2a with benzaldehyde, which could be formed by oxidation of the diazo intermediate, trans-imination between 2a and the corresponding hydrazone of 5, or hydrolysis of the latter.

Surprisingly, the use of different batches of 5 led to differences in the yields obtained. For some batches of 5 (denoted as “batches 1” in the ESI†) rather high yields were obtained at mild reaction temperatures, while for other batches of 5 (denoted as “batches 2” in the ESI†) only poor yields (generally <35%) were obtained under similar conditions (i.e. runs at 55 °C for 20 hours). In the latter case significant amounts of the starting compound 5 were detected in the reaction mixture by 1H NMR spectroscopy, thus indicating that slow conversion of 5 to the required diazo species was the problem. The slow thermolysis of some batches of 5 as compared to others at low temperatures (i.e. 55 °C) is most likely related to morphology differences between the different batches of this poorly soluble solid material. For the less reactive batches, a reaction temperature of 80 °C was required to obtain moderate yields of the desired products (see ESI, Table S1†).

β-Lactam synthesis via catalytic ketene formation

β-Lactams are medicinally important structures and versatile building blocks for other valuable compounds. A number of methods are available to synthesize these compounds, with [2 + 2] Staudinger ketene-imine cyclization being among the most extensively used and studied protocols. Recently, novel synthetic protocols were developed that enhance the synthetic applicability of Staudinger-type β-lactam synthesis, making use of in situ generated ketenes via catalytic carbylation of diazo-derived carbenes in one-pot synthetic protocols to prepare the respective β-lactams. This was shown to be a useful alternative to more traditional β-lactam synthesis. The next step in this field is to develop enantioselective versions of these reactions. However, this is not so trivial, as the ketene intermediates seem to have low affinity for the catalysts applied thus far. Hence we studied the Rh[PNN] complexes as catalysts for this reaction.

Using similar conditions as the recently reported literature, we tested the catalytic activity of the complexes in the reaction using N-benzylidenemethanamine 8a as the imine substrate. Surprisingly, when EDA was used as the substrate, the complexes B or E, identified as supreme catalysts in catalytic ketene synthesis for amide formation, gave generally no formation or less than 5% yield to the expected β-lactam product, either in the presence or absence of K2CO3, with no identifiable side products and in many cases unreacted EDA detected after the reaction. The exact reason behind this behaviour is not clear, as EDA can be used in catalytic ketene formation as demonstrated by the reactions described in Table 2. Nonetheless, EDA and imine 8a are poor coupling partners in catalytic formation of β-lactams when using catalyst B or E. The Rh complexes tested are thus not compatible with the carbene precursor EDA for the corresponding β-lactam synthesis under the currently applied conditions.

In marked contrast to the results obtained with EDA, using the N-tosyldihydrozone salt 5 as the carbene precursor led to more selective reactions, producing the β-lactam product 9a (Table 3). In the series of complexes A–C and E, complex B gave the highest yield of the desired β-lactam product 9a (67.7%), while E (which was one of the best performing catalysts for the reactions described in Table 2) gave only a moderate yield of 33.0%. Complex A gave no formation of β-lactam, while complex C led to low yield and 23.1% of the (free) phenyl ketene, according to 1H NMR spectroscopy. It should be noted that 5 is also a relative strong base, hence the corresponding Rh complexes are expected to exist in their NH-deprotonated neutral amido forms in the catalytic reaction, even in the absence of additional base. In all cases, the trans-configured β-lactam was the predominant isomer, while the cis-isomer was either not detected or present as a minor product (assignments based on literature). The trans–cis stereo-selectivity has been a poorly understood and controversial topic in the Staudinger reaction. Previous studies have shown that the stereo-selectivity may be related to isomeriza-
tion of the imine or zwitterionic intermediate, and is determined by many factors such as solvent and temperature, but most importantly the substituents of both the ketene and the imine. As higher trans/cis ratios of the product 9a were generally observed with the rhodium catalyst system than for non-catalysed systems29 and those with Pd14 and Co14 systems under similar or identical conditions, we believe that the cyclization process is also metal-catalysed.30 Metal-involvement in the \([2 + 2]\) ketene-imine cyclization has been suggested for ketenes generated from carbonylation of Fischer carbenes.31 As such, this is a promising observation, stimulating further research in the development of enantioselective reactions.

Variation of the \(\text{para}\)-substituent on the phenyl ring of imine 8 has an effect on the yield of products 9, but in all cases moderate to excellent activities for coupling with the \(\text{in situ}\) generated ketene were observed (see ESI, Table S2†).

Table 3  Rhodium catalyst screening for \(\beta\)-lactam 9a synthesis from 5 and 8a

| Entry | Catalyst | Yield of 9a (%) | Yield of 10 (%) |
|-------|----------|----------------|----------------|
| 1     | A        | 0              |                |
| 2     | B        | 67.7           | 23.1           |
| 3     | C        | 7.2            |                |
| 4     | E        | 33.0           |                |

Catalytic ketene imine synthesis from carbene precursor 5 and \(\text{tert}\)-butyl isocyanide 11

Ketene imines, the nitrogen analogues of ketenes (\(\text{e.g.} \) 12 in Scheme 6), represent an important class of reactive species and useful synthetic intermediates, which are able to undergo nucleophilic coupling or cyclization reactions for the production of various pharmaceutically valuable molecules, \(\text{e.g.}\) substituted isoquinolines and pyridines.25,26,27 As the rhodium complex B showed good catalytic activities in mediating ketene formation \(\text{via}\) carbonylation of carbenes, we were interested to extend the synthetic concept to catalytic ketene imine synthesis from carbenes and isocyanides, which are isoelectronic to CO. As this reaction has thus far mostly been studied stoichiometrically,17 development of catalytic methods should be practically useful,18 potentially allowing a wide substrate scope and an alternative mild condition route to traditional ketene imine synthesis.

While EDA turned out to be an unsuitable carbene precursor for the reaction (no ketene imine was observed after a series of reaction optimizations with and without \(\text{K}_2\text{CO}_3\)), the hydrazone salt 5 in combination with \(\text{tert}\)-butyl isocyanide 11 gave 50.7% yield of the phenyl ketene imine 12, catalysed by complex B at 55 °C overnight (see ESI, Table S3†). Excess 11 is beneficial, producing ketene imine 12 in a higher yield (entries 1 and 2, Table S3†). To the best of our knowledge, this is the first example of catalytic synthesis of any ketene imine from a carbene precursor and an isocyanide. Different batches of 5 again led to irreproducibility of yields and a need to use a higher reaction temperature to covert certain batches of tosyl hydrazone salt 5 to the diazo compound (see Table S3†).

We next investigated the one-pot synthesis of 2-phenylacetimidamide 13 by adding an amine nucleophile 2b to the \(\text{in situ}\) generated ketene imine (Scheme 6), which led to 30.0% yield of the desired product 13 along with 64.3% of the intermediate ketene imine 12, despite a reaction time of 44 hours. This possibly relates to the lower electrophilicity of ketene

Scheme 6  Acetimidamide 13 synthesized by one-pot catalytic ketene imine formation from 5 and 11 and subsequent trapping of ketene imine 12 by aniline 2b.
imines as compared to ketenes, or (perhaps more likely) serves
as an indication that the coupling reaction is also catalysed by
the metal complex, which is possibly slowed down by catalyst
deactivation over the course of the reaction. Addition of two
equivalents of K₂CO₃ was expected to accelerate the coupling
process. However, while the ketene imine 12 was not observed
after 18 hours, the 2-phenylacetimidamide 13 was obtained
only in 25.1% yield, and the imine product 7b was obtained as
the major product in 49.8% yield. Further optimizations by
varying the base, solvent and ratio of agents could result in
selectivity improvements, but this was not attempted because
it appears right now that the Rh[PNN] systems are too sensitive
to allow high conversions of 12 to 13 in one-pot transfor-
mations using the same catalyst.

Mechanistic studies

DFT calculations on ketene formation and β-lactam
formation. DFT-D3 calculations at the BP86/def2-TZVP level
were performed in order to examine the possible mechanisms
catalytic ketene formation, as well as the follow-up ring-
closure steps between the ketene intermediate and the imine
substrate. One of the main questions regarding the mechan-
ism of the Rh-catalysed β-lactam formation is whether the
overall process involves catalytic ketene formation followed by
un-catalysed coupling of the imine with the free ketene, or
whether the imine-ketene coupling step is also Rh-catalysed
proceeding via a rhodium-coordinated ketene moiety. This is
important to assess the feasibility of developing any enanti-
selective protocols. Another important question we tried to
answer with DFT is whether ketene formation by carbylation of the
metallocarbene intermediate involves the carboxyl
ligand that is already coordinated to rhodium as a ligand
(inner-sphere mechanism) or proceeds via external CO attack
at the carbeneoid intermediate (outer-sphere mechanism). The
ketene-imine [2 + 2] cyclization step can also differ with
respect to whether the imine coordinates to the metal centre
prior to reaction or not. Hence, several possible pathways
were studied with DFT methods: A completely inner-sphere pathway
Pₙ₁ with both ketene formation and ring-closure of the ketene
with the imine proceeding via internal attack; A completely
outer-sphere pathway P₀₀₀, with both steps involving external
attack of substrates to coordinated carbene and ketene inter-
mediates; and mixed pathways Pₙₒ and Pₒ₀. In the applied lab-
elling the first I/O subscript denotes inner- or outer-sphere
pathway for CO insertion step, while the second subscript
denotes an inner- or outer-sphere pathway for ketene-imine
coupling (see Scheme 7 and Scheme S1 in the ESI†).

The catalytically active Rh-PNN species may be present
either in their neutral NH-deprotonated amido form, or in
their cationic non-deprotonated amine form. Both possibilities
were investigated. The pathways and species involving cationic
Rh-complexes with neutral PNNH amine ligands are denoted
with an NH label (⁴⁰P pathway), while the pathways and
species involving neutral amido complexes with anionic
(N-deprotonated) PNN⁻ ligands are labelled with an N label
plexes as well as for the neutral amido species. However, the barriers for these competing pathways are very similar.

Since the applied empirical dispersion corrections might be somewhat overestimated and at the same time the computed entropy effect of the two processes are widely different with one process being intramolecular and the other being intermolecular (for which computed entropy factors are overestimated), any reliable distinction between these inner-sphere and outer-sphere pathways can probably not be made on the basis of DFT. Therefore both inner- and outer-sphere pathways for formation of the (coordinated) ketene can be considered viable, and hence both computed pathways are discussed below.

**Inner-sphere ketene formation.** The barriers for internal attack of CO to form the ketene species INT3 (structure of INT3 shown in Fig. 3) was calculated to be +12.9 and +13.5 kcal mol\(^{-1}\) for the amido and the amino form, respectively. The metal complexes are correspondingly neutral and cationic, the labels were omitted for clarity. *For INT2, ’b’ indicates the carbene moiety is in a basal position; ’a’ indicates the carbene moiety is in the axial position.

---

**Scheme 7** DFT calculated (DFT-D3, BP86, def2-TZVP) pathways for β-lactam formation via catalytic generation of ketenes from rhodium-carbenoids (isodesmic, balanced reactions). Free energies (\(\Delta G^{298}\)) in kcal mol\(^{-1}\). All energies (also those of the transition states) are reported relative to species INT0. *N* and NH denote the amido and amino forms, respectively, of the intermediates. The metal complexes are correspondingly neutral and cationic, the labels were omitted for clarity. *For INT2, ’b’ indicates the carbene moiety is in a basal position; ’a’ indicates the carbene moiety is in the axial position.
when adopting a Rh-$\eta^2$-CC$_\text{ketene}$ coordination mode rather than $\eta^2$-CO$_\text{ketene}$ or $\kappa^1$-O$_\text{ketene}$ modes (+3.9 and +34.1 kcal mol$^{-1}$ higher for the amido and +4.9 and +21.4 kcal mol$^{-1}$ higher for the amine species, respectively), see Fig. 3. The ketene deviates from the coordination plane, with the C$_p$ trans to the pyridine (for the amido INT3, $\angle$N$_\text{py}$-Rh-C$_p$ = 166.0°, $\angle$N$_\text{py}$-Rh-C$_a$ = 126.9°). The bonding situation is best described as a rhoda-aza-cyclopropane structure with a formal RhIII oxidation state, indicated by the bond lengths in the metallaacyclic fragment (for example, C$_p$-C$_b$ bond lengths are 1.450 and 1.432 Å for the amido and amine form, respectively, showing single bond character). The coordination preference for $\eta^2$-CC$_\text{ketene}$ over $\eta^5$-CO$_\text{ketene}$ fashion is expected according to the HSAB theory, as the ketene C==C moiety is “softer” than the C==O unit. The amido ketene species is 6.7 kcal mol$^{-1}$ more stable than the amine derivative, in agreement with enhanced metal-to-ligand back-donation in the former.

**Outer-sphere ketene formation.** External attack of CO to INT2 leads to formation of ketene adduct INT6. This species is quite similar to ketene adduct INT3, but contains an additional carbonyl ligand. The rhodium centre in INT6 was calculated to adopt a distorted trigonal bipyramidal coordination geometry (structure of INT6 shown in Fig. 4), with CO, the pyridine and the ketene occupying the equatorial positions. The metal is best described as a rhodium(III) centre in a rhoda-aza-cyclopropane structure, similar to that in INT3. In TS2-6, the external CO molecule approaches the Rh-carbene fragment, and interacts with Rh to form a distorted 6-coordinate 20e-like transition state geometry. However, TS2-6 does not produce a stable 20e bis-carbonyl carbene intermediate (all attempts to optimize the geometry of such species either produced INT6 by CO insertion into the carbene moiety or INT2 by CO dissociation). Due to a weak interaction between the incoming CO molecule and the carbene moiety in TS2-6, the transition state directly produces INT6 by concerted insertion of the incoming CO molecule into the Rh-carbene moiety (as confirmed by following the IRC).

Two other isomeric forms were calculated to be slightly higher in energy, one being the Rh-$\eta^3$-CO$_\text{ketene}$ isomer (+0.4 kcal mol$^{-1}$ for the amido form) and the other having the CO coordinated trans to the pyridine and the ketene loosely bound at the axial position (+3.4 kcal for the amido form), suggesting possible ketene slippage and partial dissociation from the metal.

External attack of CO to INT2 to form ketene adduct INT6 is a process with a somewhat lower barrier (+8.5 and +11.7 kcal mol$^{-1}$ for the amido and the amine forms, respectively) than the inner-sphere pathway to form INT3. Regarding the overestimation of the entropy penalty, these barriers may in reality be even lower. On the other hand the empirical dispersion effects in the approach of the CO ligand may be overestimated, and considering the rather small relative energy differences concerning these barriers, this makes it rather difficult to judge if the route via TS2-3 or via TS2-6 is the preferred pathway. Hence, we consider both pathways viable.

**Relevance of ketene intermediates INT3 and INT6.** The outer-sphere pathway leading to INT6 is clearly more exothermic than the inner-sphere reaction producing INT3. In addition, formation of intermediate INT6 by simple coordination of an additional carbonyl ligand to INT3 is likely to occur under the applied experimental reaction conditions (CO pressure). Hence, formation of INT6 is expected, both for the inner-sphere and for the outer-sphere pathways, and the equilibrium between these two species should lay strongly on the side of INT6. In that perspective, follow-up reactivity with the imine substrate could perhaps be expected to proceed preferably from the lower energy ketene intermediate INT6 rather than from INT3. Nonetheless, we also considered the pathways from INT3 relevant for $\beta$-lactam formation, as this intermediate is
less “saturated” and gives access to other substrate adducts and hence different pathway with potentially lower barriers.

**Follow-up reactivity of the ketene intermediates INT3 and INT6 with the imine substrate**

One possible pathway leading to β-lactam formation after formation of the ketene adducts INT3 and INT6 is ketene dissociation followed by an uncatalysed coupling step between the free, uncoordinated ketene and the imine substrate. However, according to DFT the uncatalysed coupling of the free (uncoordinated) ketene and imine substrates (see Scheme 8) is associated with a very high barrier of 39.7 kcal mol⁻¹. Importantly, the computed Rh-catalysed imine-ketene coupling steps in pathways PII and POO discussed below have much lower barriers (all computations performed using the same level of theory: DFT-D3, BP86, def2-TZVP), strongly suggesting that the final imine-ketene coupling steps of the β-lactam formation reaction are also Rh-catalysed.

From the neutral and cationic ketene intermediates INT3 and INT6 the possible pathways for Rh-catalysed β-lactam formation further diverge, and four different routes (partly interconnected by possible CO coordination/dissociation steps) were considered relevant for the formal imine [2 + 2] cyclization with the metal-bound ketene: The PII and POO pathways each proceed from ketene intermediate INT3 and concern inner-sphere and outer-sphere pathways for coupling of the imine reagent with the coordinated ketene ligand, respectively. In the pathways PII the imine first coordinates to the metal before it couples to the ketene C=C bond, whereas in the POO pathway the imine directly attacks the coordinated ketene ligand as an external nucleophile. The POO and POI pathways each proceed from ketene intermediate INT6, and describe similar inner-sphere and outer-sphere pathways for coupling of the imine with the ketene ligand of INT6. These latter pathways are thus influenced by the presence of an additional CO ligand bound to rhodium. A short description of the two more plausible pathways PII and POO follows below, while the alternative, but energetically less favourable pathways POI and PII are shown and discussed in some detail in the ESI (Scheme S1†).

**Pathway PII**: Coordination of the imine substrate to INT3 is slightly exergonic for both the cationic amine complex and the neutral amido species, producing intermediates INT4. For the neutral amido form of the imine-coordinated intermediate INT4 the ketene coordinates as an acetyl ligand with a κ¹-Cα coordination pattern, while in the cationic amine form of INT4 the Rh-η¹-C(CG)ketene-coordination mode is maintained. Intramolecular ring-closure via TS4-5 involving C–C bond formation converts INT4 into the five-membered metallocyclic intermediates INT5, which produce the β-lactam product after successive reductive cyclization (TS5-0). For both the cationic amine and the neutral amido species, the TS4-5 (N: +14.2 kcal mol⁻¹; NH: +12.3 kcal mol⁻¹) and TS5-0 (N: +15.4 kcal mol⁻¹; NH: +12.6 kcal mol⁻¹) free energy barriers are very accessible, but the barriers for the cationic amine species are slightly lower than those of the neutral amido derivatives. In both cases the barriers for this pathway are much lower than the total barrier of the rate limiting diazo activation step (N: +21.7 kcal mol⁻¹; NH: +29.0 kcal mol⁻¹). Release of the product and association of CO regenerates the starting complex INT0, thus closing the catalytic cycle.

**Pathway POO**: The outer-sphere ketene-imine cyclization was calculated to occur in a concerted [2 + 2] step, directly at the coordinated ketene moiety of INT6 contrasting all other pathways involving stepwise couplings. This concerted reaction step (INT6 → TS6-0 → INT0 + β-lactam) directly produces the β-lactam product with regeneration of the starting complex INT0. It has a very low barrier for the cationic amine species (ΔG‡ = +3.1 kcal mol⁻¹), while it has a significant but nonetheless very accessible barrier for the neutral amido species (ΔG‡ = 15.2 kcal mol⁻¹). Considering that the rate limiting diazo activation step via TSI-2 has a lower barrier for the deprotonated form of the catalyst, the barrier for the neutral amido species seems however most relevant in this POO pathway. This reaction pathway is a viable route for catalytic β-lactam product formation, especially considering the relative stability of intermediate INT6 as compared to INT3.

**Pathway POI and POI**: Two alternative pathways POI and POII were explored (see Scheme S1 in the ESI†), but both proceed via much higher barriers than pathways PII and POO. Pathway POI proceeds via direct attack of the imine nitrogen atom at the ketene moiet of INT3 followed by stepwise ring closing process, with exceedingly high overall barriers from INT3 (N: INT3 → TS8-0, ΔG‡ = +40.8 kcal mol⁻¹; NH: INT6 → TS8-0, ΔG‡ = +32.6 kcal mol⁻¹), making this route much less favourable than pathway PII. For pathway POII, the first transition state for stepwise ring closing process represents rather high overall barriers from intermediate INT6 (INT6 → TS9-10: N: ΔG‡ = +25.3 kcal mol⁻¹; NH: ΔG‡ = +19.6 kcal mol⁻¹), which is clearly less favorable than pathway POO. For more details about pathway POI and POII, see the ESI†.

**Brief summary of the DFT calculations**

The combined DFT calculations can be summarized as follows: The activation of the diazo compound to form the carbene intermediate INT2 appears to be the rate-limiting step of the reaction, and this step is faster upon amine deprotonation of the PNN ligand of the catalyst. Hence (in agreement with the experimental observations), it seems that the reactions preferably take place with the catalyst in its amine deprotonated form. As such, in the remaining discussion below the
energetic barriers listed are limited to those concerning the most relevant neutral amido species.

From INT2, the saturated and unsaturated ketene intermediates INT6 and INT3 can be formed, with INT6 calculated to be lower in energy. From INT3 pathway \( P_B \) is the lowest barrier route to \( \beta \)-lactam formation, while for INT6 the lowest barrier route is the \( P_{OO} \) pathway (\( \Delta G^* = +15.2 \text{ kcal mol}^{-1} \)). Considering the higher stability of INT6, the overall barriers along the \( P_B \) pathway are somewhat higher than along the \( P_{OO} \) pathway (\( \Delta G^* = +22.0 \text{ kcal mol}^{-1} \) versus +15.2 kcal mol\(^{-1} \)). However, overestimated dispersion corrections could play a role in favoring the \( P_{OO} \) pathway over the \( P_B \) pathway, and hence both pathways remain viable routes to \( \beta \)-lactam formation. The \( P_O \) and \( P_{Oi} \) pathways can be safely excluded based on their relatively overall energy barriers as compared to the \( P_B \) and \( P_{OO} \) pathways, respectively (see Scheme S1†).

Stoichiometric experimental studies aimed at showing formation of ketenes by internal CO attack

In order to get experimental information for ketene formation, we first investigated the possibility for internal CO migration to the Rh-carbenoid moiety to form the ketene product. When two equivalents of EDA (1) were added to a \( \text{CD}_2\text{Cl}_2 \) solution of complex B at room temperature, no reaction except for dimerization of the diazo-evolved carbenoid was observed in an overnight experiment (two isomers of diethyl fumarate giving two sharp singlets at 6.2 and 6.8 ppm, respectively, see ESI, Fig. S2†). When two equivalents of \( N \)-tosyl hydrazone salt 5 were added to complex B in \( \text{CD}_2\text{Cl}_2 \), complex B was immediately deprotonated, accompanied with a colour change from yellow to purple-red. Heating the solution to 55 °C for 1 hour did not produce any phenylketene. In another reaction, one equivalent of DBU was added to deprotonate the NH moiety of the PNN ligand of complex B prior to the addition of the \( N \)-tosyl hydrazone salt 5, to avoid generation of the organic \( N \)-tosyl hydrazone precursor, which would interfere in the \( ^1\text{H} \) NMR spectrum. Heating the reaction mixture to 55 °C for five hours gave rise to a singlet at 4.88 ppm in the \( ^1\text{H} \) NMR spectrum (see ESI, Fig. S4 and S5†), which indeed indicates formation of the ketene species. Other signals are slightly broadened and hence not clear. In the \( ^{31}\text{P} \) NMR spectrum, one doublet at 49.85 ppm with a small \( J_{\text{HH}} \) coupling constant of 137.8 Hz suggested that the PNN ligand is probably in the amido form.39 This result indicates that inner-sphere CO insertion is indeed a viable possibility under the applied reaction conditions to form the ketene fragment, but whether or not this process is truly involved in the catalytic routes is less clear.

Conclusions

In summary, we have synthesized a series of rhodium complexes featuring new secondary amine containing PNN ligands. Complex B and E showed good activity in catalytic ketene synthesis involving carbynolation of carbenes. Amides and \( \beta \)-lactams can be synthesized in one-pot reactions proceeding via in situ generated ketene intermediates. A ketene imine has also been synthesized in a catalytic manner by reaction of a carbenoid with an isocyanide.

DFT computational studies suggest that activation of the diazo compound to generate the rhodium-carbenoid intermediate is the rate-determining step of the catalytic reaction, with the neutral amido complex being more reactive than the cationic amine complex. This is in agreement with the experimental studies, showing that the use of basic conditions (either by using \( \text{K}_2\text{CO}_3 \) or using basic tosyl hydrazone salts as substrates) is beneficial. Outer-sphere CO insertion is computed to be slightly favoured over the inner-sphere mechanism. Preliminary experimental studies show that inner sphere CO insertion to form ketene is also possible, but whether or not this process is truly involved in the catalytic routes is less clear. Additional spectrometric and kinetic studies are needed to unveil further details about the mechanism of these reactions. Follow-up coupling mechanisms most likely proceed via either the \( P_{OO} \) or \( P_B \) pathways depicted in Scheme 7, with the \( P_{OO} \) pathway being slightly favoured over the \( P_B \) pathway according to DFT.

Experimental details

General methods

All reactions were carried out under an argon atmosphere using standard Schlenk techniques or in a glovebox unless noted otherwise. With exception of the compounds given below, all reagents were purchased from commercial suppliers and used without further purification. \( N \)-Methyl-1-(6-methylpyridin-2-yl)methanamine (for synthesis of a)30 and \( N \)-(6-methylpyridin-2-yl)methylaniline (for synthesis of b)41 were synthesized from 6-methylpicinaldehyde according to literature procedures. 2-(Chloromethyl)-6-(di-tert-butylphosphino)-methylpyridine-BH\(_4\) (for the synthesis of d) and 2-(chloromethyl)-6-(diisopropylphosphino)methylpyridine-BH\(_4\) (for the synthesis of e and c) were synthesized from 2,6-bis(chloromethyl)pyridine according to a reported procedure.42 Complex D was synthesized according to a reported literature procedure.22 THF, dioxane, pentane, and diethyl ether were distilled from sodium (benzophenone as indicator) under nitrogen. \( \text{CH}_2\text{Cl}_2 \) and methanol were distilled from CaH\(_2\) under nitrogen. \( N \)-Tosylhydrazone sodium salts were synthesized according to published procedures.43,44 6-Methylpicinaldehyde and 2,6-bis(chloromethyl)pyridine were purchased from TCI Europe. Picinaldehyde and ethyl diazoacetate (EDA) were purchased from Aldrich (up to 15% dichloromethane, actual content determined by NMR). NMR spectra \( ^1\text{H}, ^{31}\text{P}(^1\text{H}) \) and \( ^{13}\text{C}(^1\text{H}) \) were measured on a Bruker AMX 400 spectrometer at 25 °C, unless noted otherwise. IR spectra were recorded on a Nicolet Nexus FT-IR spectrometer. HR-MS were obtained using a time-of-flight JEOL AccuTOF LC-plus mass spectrometer (JMS-T100LP).
Ligand a. N-Methyl-1-(6-methylpyridin-2-yl)methanimine (680.0 mg, 4.99 mmol) was dissolved in diethyl ether (Et₂O; 30 mL) and cooled to −78 °C. nBuLi (1.6 M in hexane, 6.30 mL, 10.08 mmol) was slowly added, dropwise under stirring. The reaction was stirred at −78 °C for 30 minutes and subsequently allowed to warm-up slowly to 0 °C, at which temperature the mixture was stirred for 3 hours. In parallel, chlorodiphenylphosphine (1.79 mL, 9.99 mmol) was dissolved in Et₂O (30 mL) and was cooled to −78 °C. The former reaction mixture was cooled again to −78 °C and cannulated slowly to the latter solution. The reaction mixture was allowed to warm-up slowly to room temperature and stirred overnight. To quench the reaction, a 1 M HCl solution (40 mL) degassed was added and the reaction mixture was stirred for 2 hours. Sodium carbonate (Na₂CO₃) was added slowly until a pH of approx. 8. The aqueous solution was extracted with Et₂O (3 × 40 mL). The Et₂O extracts were combined and dried over Na₂SO₄. The solid was filtered off and the Et₂O solvent removed in vacuo. A light-yellow oily product was obtained after purification by column chromatography under argon (eluent: hexane, then DCM). Yield: 267.0 mg (16.7%). ¹H NMR (400 MHz, CD₂Cl₂, ppm): δ 7.52–7.44 (m, 4H Ph), 7.10–7.02 (m, 6H Ph), 6.98 (td, J = 7.7, 2.5 Hz, 1Hpy), 6.83 (d, J = 7.1 Hz, 1Hpy), 6.69 (d, J = 7.7 Hz, 1Hpy), 3.71 (s, 2H Ph), 3.60 (d, J = 2.1 Hz, 2H Ph), 3.60 (d, J = 2.1 Hz, 2H Ph). ³¹P{¹H} NMR (161 MHz, CD₂Cl₂, ppm): δ −10.84 (s). ¹³C{¹H} NMR (100 MHz, CD₂Cl₂, ppm): δ 160.07 (s, Cpy), 158.03 (d, J = 7.9 Hz, Cpy), 139.49 (s, C₅py), 139.33 (s, C₃py), 136.24 (s, Cpy), 133.42 (d, J = 19.1 Hz, 2Cpy), 128.73 (s, Cpy), 128.60 (d, J = 6.5 Hz, 2Cpy), 121.64 (d, J = 6.1 Hz, Cpy), 119.42 (d, J = 2.3 Hz, Cpy), 57.38 (s, PyCH₂N), 39.06 (d, J = 17.3 Hz, PyCH₂P), 36.09 (s, CH₂). HRMS (ESI, 243 K, DCM): m/z 641.2975 (2M + H⁺), Calcd m/z 641.2957. Ligand a was detected as a (H-bonded) dimer (M⁺H).

Ligand b. A similar procedure as used for the synthesis of ligand a was followed, starting from N-(6-methylpyridin-2-yl)-methylaniline (641.0 mg, 3.23 mmol). Ligand b was obtained as light-yellow sticky oil. Yield: 243.6 mg (19.7%). ¹H NMR (400 MHz, CD₂Cl₂, ppm): δ 7.47 (td, J = 7.3, 1.8 Hz, 4Hpy), 7.19–7.13 (m, 2Hpy), 6.90 (t, J = 7.7 Hz, 1Hpy), 6.76 (tt, J = 7.5, 1.2 Hz, 1Hpy), 6.67 (d, J = 7.6 Hz, 1Hpy), 6.60 (d, J = 7.9 Hz, 1Hpy), 6.60 (d, J = 7.9 Hz, 1Hpy), 6.54–6.50 (m, 2Hpy), 4.46 (br s, 1H NH), 4.10 (d, J = 4.7 Hz, 2H Ph-CH₂), 3.59 (s, 2H Ph-CH₂). ³¹P{¹H} NMR (161 MHz, CD₂Cl₂, ppm): δ −11.02 (s).

Complex A. A solution of ligand a (76.5 mg, 0.240 mmol) in methanol (2 mL) was added to a solution of [Rh(CO)₂(p-Cl)] (46.6 mg, 0.120 mmol) in methanol (3 mL), followed by addition of NH₄PF₆ (78.2 mg, 0.480 mmol). The solution was stirred for one hour and the solution was concentrated to ±3 mL under vacuum. The brownish-yellow precipitate was collected by filtration and washed with a small amount of cold methanol and dried in vacuo. Complex A was obtained as a crystalline material by storing a concentrated MeOH/H₂O solution of A at 0 °C. Yield: 103.2 mg (72.1%). ¹H NMR (400 MHz, CD₂Cl₂, ppm): δ 7.92 (td, J = 7.9; 1.1 Hz, 1Hpy), 7.74–7.66 (m, 3Hpy + 1Hpy), 7.60–7.48 (m, 7Hpy), 7.44 (d, J = 7.9 Hz, 1Hpy), 4.79 (dd, J = 16.5; 2.4 Hz, 2H Ph-CH₂), 4.39–4.42 (m, 2H Ph-CH₂), 4.32 (s, 1H NH), 3.09 (br s, 3H Me); ³¹P{¹H} NMR (400 MHz, MeOD-d₄, ppm): δ 8.00 (t, J = 7.9 Hz, 1Hpy), 7.82–7.71 (m, 3Hpy + 1Hpy), 7.66 (d, J = 8.1 Hz, 1Hpy), 7.61–7.49 (m, 7Hpy), 6.25 (bm, 1H NH), 4.71 (dd, J = 16.7; 5.8 Hz, 1Hpy-CH₂), 4.53 (dd, J = 11.7; 7.1 Hz, 2Hpy-CH₂), 4.39 (dd, 16.8, 6.5 Hz, 1Hpy-CH₂), 3.02 (m, 3H Me); ³¹P{¹H} NMR (161 MHz, CD₂Cl₂, ppm): δ 52.87 (d, J₁H₂b-P = 152.3 Hz, major), 52.66 (d, J₁H₂b-P = 152.6 Hz, minor); ³¹P{¹H} NMR (161 MHz, MeOD-d₄, ppm): δ 52.55 (d, J₁H₂b-P = 150.2 Hz). ¹³C{¹H} NMR (100 MHz, MeOD-d₄, ppm): δ 192.22 (dd, J = 73.4; 18.0 Hz, CO), 163.85 (s, J = 2.1 Hz, Cpy₂), 161.94 (d, J = 3.1 Hz, Cpy₁), 161.86 (s, C₅py), 142.00 (s, C₃py), 133.76 (dd, J = 12.5; 7.3; 0.9 Hz, Cpy₁), 132.73 (d, J = 2.6 Hz, 2Cpy), 130.38 (d, J = 2.7 Hz, Cpy), 130.27 (d, J = 2.6 Hz, Cpy), 123.25 (d, J = 12.7 Hz, Cpy₂), 121.13 (s, Cpy₂), 62.99 (d, J = 2.1 Hz, PyCH₂N), 45.24 (d, J = 30.9 Hz, PyCH₂), 43.18 (s, CH₃). IR (CD₂Cl₂, cm⁻¹): ν = 2002.5 cm⁻¹. HRMS (ESI, 243 K, DCM): m/z 451.0435 (M⁺, Calcd m/z 451.0441).

![Image](image-url)
Complex B. A similar procedure as used for the synthesis of complex A was followed, but using ligand b (230.0 mg, 0.601 mmol) instead of ligand a. Complex B was obtained as a light yellow powder. Complex B was obtained as a crystalline material by top-layering a concentrated DCM solution of B with Et2O. Yield: 270.2 mg (68.3%). 1H NMR (400 MHz, CD2Cl2, ppm): δ 7.97 (td, J = 7.9, 1.1 Hz, 1Hpy3), 7.75–7.63 (m, 3HPh + 1Hpy3), 7.60–7.46 (d, J = 7.9 Hz, 7Hph + 1Hpy5), 7.44–7.39 (m, 2HPh), 7.37–7.33 (m, 2HPh), 7.28–7.23 (m, 1HPh) 6.71 (br d, J = 5.5 Hz, 1HNeu), 5.16 (dd, J = 16.9; 5.8 Hz, 1Hpy-CH2), 4.36 (d, J = 11.7 Hz, 2Hpy-CH3). 31P[1H] NMR (161 MHz, CD2Cl2, ppm): δ 53.48 (d, J1Rh-b = 160.0 Hz). 13C[1H] NMR (100 MHz, CD2Cl2, ppm): δ 162.50 (d, J = 4.0 Hz, CPy), 160.38 (s, CPhe), 160.33 (d, J = 2.1 Hz, CPhe), 147.15 (s, CPy), 141.19 (s, CPy), 132.99 (dd, J = 13.0; 2.6 Hz, CPhe), 132.25 (d, J = 1.8 Hz, 2CPhe), 130.29 (s, CPhe), 129.70 (d, J = 10.8 Hz, CPhe), 126.59 (s, CPhe), 120.89 (s, CPhe), 120.31 (s, CPhe), 62.69 (d, J = 1.5 Hz, PyCH2N), 45.51 (d, J = 30.6 Hz, PyCH2P); the carbon resonance signal of CO was not resolved. IR (CD2Cl2, cm⁻¹): νCO 2007.1 cm⁻¹. HRMS (ESI, 243 K, DCM): m/z 513.0581 (M⁺, Caled m/z 513.0598).

Complex C. A similar procedure as used for the synthesis of complex A was followed, but using ligand e (230.0 mg, 0.601 mmol) instead of ligand a. Complex C was obtained as a light-yellow powder. 1H NMR (400 MHz, CD2Cl2, ppm): δ 7.97 (td, J = 8.0; 0.8 Hz, 1Hpy3), 7.63 (d, J = 7.9 Hz, 1Hpy3), 7.39 (d, J = 7.9 Hz, 1Hpy5), 7.34–7.28 (m, 2HPh3,5), 7.22 (dd, J = 7.0; 2.3 Hz, 1HPh), 6.53 (br d, 1HNeu), 4.87 (m, 1Hpy-CH2), 4.60 (dd, J = 17.4; 10.0 Hz, 1Hpy-CH2), 4.47 (sep, J = 6.8 Hz, 1Hpy-CH2), NOE correlation with NPh, 3.75 (qd, J = 18.6; 10.1 Hz, 2Hpy-CH3), 3.23 (sep, J = 6.7 Hz, 1HPh-CH(CH3)2), 2.27 (sep, J = 6.9 Hz, 2HPh-CH(CH3)2), 1.46 (d, J = 6.5 Hz, 3HPh-CH(CH3)2), 1.44 (d, J = 6.5 Hz, 3HPh-CH(CH3)2), 1.39 (d, J = 6.8 Hz, 3HPh-CH(CH3)2), 1.36 (d, J = 7.2 Hz, 2HPh-CH(CH3)2), 1.33 (d, J = 6.9 Hz, 3HPh-CH(CH3)2), 1.32 (d, J = 6.4 Hz, 2HPh-CH(CH3)2), 1.30 (d, J = 6.0 Hz, 2HPh-CH(CH3)2), 1.28–1.23 (m, 4HPh-CH(CH3)2), 1.21 (d, J = 6.9 Hz, 2HPh-CH(CH3)2). 31P[1H] NMR (161 MHz, CD2Cl2, ppm): δ 84.79 (d, J1Rh-b = 152.0 Hz). 13C[1H] NMR (100 MHz, CD2Cl2, ppm): δ 189.93 (dd, J = 73.1; 19.1 Hz, CO), 161.79 (d, J = 5.2 Hz, CPhe), 160.93 (s, CPphe), 141.89 (s, CPphe), 141.46 (d, J = 1.4 Hz, CPhe or e), 141.02 (s, CPphe), 136.86 (s, CPphe or f), 138.12 (s, C(nine or e)), 127.89 (s, CPphe or 3), 126.80 (s, CPphe or 3), 124.11 (s, CPhe), 123.02 (d, J = 11.4 Hz, CPhe), 120.14 (s, CPphe), 63.46 (s, PyCH2N), 35.97 (d, J = 24.8 Hz, PyCH2P), 29.67 (s, PCpH(CH3)2), 28.93 (s, PCpH(CH3)2), 26.40 (d, J = 1.9 Hz, CH3), 26.40 (d, J = 1.9 Hz, PCH(CH3)2), 26.11 (d, J = 1.3 Hz, PCH(CH3)2), 25.80 (d, J = 2.1 Hz, PCH(CH3)2), 25.50 (d, J = 2.5 Hz, PCH(CH3)2), 25.49 (d, J = 8.2 Hz, PCH(CH3)2), 24.61 (s, ArCH(CH3)2), 23.22 (s, ArCH(CH3)2), 19.11 (d, J = 2.5 Hz, PCH(CH3)2), 18.93 (d, J = 3.4 Hz, PCH(CH3)2), 18.48 (s, ArCH(CH3)2), 17.67 (d, J = 3.4 Hz, PCH(CH3)2). IR (CD2Cl2, cm⁻¹) νCO 1999.1 cm⁻¹. HRMS (ESI, 243 K, DCM): m/z 529.1947 (M⁺, Caled m/z 529.1850).

Complex E. A similar procedure as used for the synthesis of complex A was followed, but using ligand e (230.0 mg, 0.601 mmol) instead of ligand a. Complex E was obtained as a light yellow powder. Crystalline material of complex E was obtained by top-layering a concentrated DCM solution of E with Et2O. 1H NMR (400 MHz, CD2Cl2, ppm): δ 7.92 (td, J = 7.9, 0.9 Hz, 1Hpy3), 7.54 (d, J = 7.9 Hz, 1Hpy3), 7.42 (d, J = 7.9 Hz, 1Hpy3), 7.39–7.34 (m, 2HPh), 7.29–7.25 (m, 2HPh), 7.20 (td, J = 7.2, 1.2 Hz, 1HPh), 7.10 (bm, 1HPh), 5.12 (dd, J = 17.1; 16.3 Hz, 1Hpy-CH2), 4.71 (dd, J = 17.1; 5.1 Hz, 1Hpy-CH2), 3.65 (dd, J = 10.0; 4.2 Hz, 2Hpy-CH2), 2.27–2.12 (m, 2HPh-CH(CH3)2), 1.30 (d, J = 7.1 Hz, 2HPh-CH(CH3)2), 1.22 (d, J = 7.1 Hz, 2HPh-CH(CH3)2), 1.21 (d, J = 7.0 Hz, 2HPh-CH(CH3)2), 1.30 (d, J = 7.1 Hz, 2HPh-CH(CH3)2). 31P[1H] NMR (161 MHz, CD2Cl2, ppm): δ 83.81 (d, J1Rh-b = 152.8 Hz). 13C[1H] NMR (100 MHz, CD2Cl2, ppm): δ 189.97 (dd, J = 73.2; 18.6 Hz, CO), 162.35 (d, J = 2.0 Hz, CPy2), 161.47 (t, J = 4.2 Hz, CPy2), 147.15 (d, J = 1.7 Hz, CPhe), 140.00 (s, CPphe), 130.17 (s, 2CPh2), 126.35 (s, CPphe), 122.58 (d, J = 11.3 Hz, CPhe), 120.75 (s, 2CPh3,5), 119.95 (s, CPphe), 62.41 (d, J = 1.8 Hz, PyCH2N), 35.94 (d, J = 24.5 Hz, PyCH2P), 26.02 (dd, J = 29.5, 2.0 Hz, PCH(CH3)2), 18.12 (d, J = 13.6 Hz, PCH(CH3)2). IR (CD2Cl2, cm⁻¹) νCO 1998.6 cm⁻¹. HRMS (ESI, 243 K, DCM): m/z 445.0941 (M⁺, Caled m/z 445.0911).
**In situ ketene synthesis by carbene carbynolation**

In a typical carbynolation experiment, a stainless steel autoclave (150 mL) suitable for seven reaction vessels (equipped with Teflon mini-stirring bars) was used to perform parallel reactions. Each vial was charged with carbene precursor (EDA 1 or N-tosylhydrazone sodium salt 5, 0.15 mmol), amine nucleophile (0.30 mmol), rhodium catalyst (0.0075 mmol), internal standard 1,3,5-trimethoxybenzene (0.015 mmol) and solvent (3 mL). Before starting the catalytic reactions, the charged autoclave was purged (5×) with 20 bar of CO and then pressurized to the desired pressure. The autoclave was heated in an oil-bath with the vials being stirred overnight. After the reaction, the autoclave was cooled to 0 °C and vented to 1 atm.

Ketene imine synthesis involving carbene–isocyanide coupling

A 25 mL Schlenk vessel was charged with N-tosylhydrazone sodium salt 5 (0.15 mmol), rhodium catalyst (0.0075 mmol), internal standard 1,3,5-trimethoxybenzene (0.015 mmol), toluene (5 mL) and tert-butyl isocyanide (0.75 mmol). The Schlenk vessel was then sealed and heated in an oil-bath overnight. After the reaction, around 2.5 mL was taken out of the reaction mixture, and the solvent was removed via rotary evaporation. The residue was dissolved in CDCl₃ or CH₂Cl₂ and filtered when necessary for ¹H NMR and GC-MS analysis, respectively. The conversion and yield for each reaction were calculated based on integration of the ¹H NMR signals of the corresponding species relative to that of the internal standard. Product assignment followed assignments presented in literature.¹⁴e

**X-ray crystal structure determination of complex A**

Reflections were measured on a Bruker Kappa ApexII diffractometer with sealed tube and Triumph monochromator (λ = 0.71073 Å) at a temperature of 150(2) K up to a resolution of (sin θ/λ)max = 0.81 Å⁻¹. The intensities were integrated with the EVA15 software.⁴₅ Multiscan absorption correction and scaling was performed with SADABS⁴⁶ (correction range 0.67–0.75). The structure was solved with Patterson superposition methods using SHELXT⁴⁷ Least-squares refinement was performed with SHELXL-2013.⁴¹ Against F² of all reflections. Non-hydrogen atoms were refined freely with anisotropic displacement parameters. The coordinated amino nitrogen was disordered over two positions with a ratio 0.884(6):0.116(6). All hydrogen atoms were located in difference Fourier maps. The hydrogen atom at N₂ was refined freely with an isotropic displacement parameter, all other H-atoms were refined with a riding model. Geometry calculations and checking for higher symmetry was performed with the PLATON program.⁴⁹

X-ray crystal structure details of complex A

[C₅H₇N₂]{OPRh}[(PF₆)₃CH₂OH, Fw = 628.29, yellow block, 0.57 × 0.35 × 0.18 mm³, triclinic, P1 (no. 2), a = 9.70447(19), b = 9.77001(15), c = 14.1603(3) Å, α = 83.358(1), β = 74.636(1), γ = 74.636(1), V = 1246.84(4) Å³, Z = 2, Dₓ = 1.674 g cm⁻³, μ = 0.88 mm⁻¹. 41,801 reflections were measured up to a resolution of (sin θ/λ)max = 0.81 Å⁻¹. 10,952 reflections were unique (Rint = 0.015), of which 10,239 were observed (I > 2σ(I)). 330 parameters were refined with 1 restraint (C–N distance of the disordered group). Rint/WR²[I > 2σ(I)] = 0.0221/0.0567. R₁/wR₁[all refl.]: 0.0243/0.0577. S = 1.057. Residual electron density between –0.53 and 0.61 e Å⁻³. CCDC 1424620.

X-ray crystal structure determination of complexes B and E

X-ray intensities were measured on a Bruker D8 Quest Eco diffractometer equipped with a Triumph monochromator (λ = 0.71073 Å) and a CMOS Photon 50 detector at a temperature of 150(2) K. Intensity data were integrated with the Bruker APEX2 software.⁵⁰ Absorption correction and scaling was performed with SADABS.⁴⁶ The structures were solved with the program SHELXL.⁵⁰ Least-squares refinement was performed with SHELXL-2013 against F² of all reflections. Non-hydrogen atoms were refined with anisotropic displacement parameters. The H atoms were placed at calculated positions using the instructions AFIX 13, AFIX 43 or AFIX 137 with isotropic displacement parameters having values 1.2 or 1.5 times Ueq of the attached C atoms.

X-ray crystal structure details of complex B

[C₅H₇N₂]_{2}OPRh PF₆, Fw = 658.31, yellow block, 0.389 × 0.319 × 0.112 mm³, Monoclinic, P2₁/c, a = 10.6439(13), b = 11.6245 (14), c = 21.782(2) Å, β = 100.416(2)°, V = 2650.7(5) Å³, Z = 4, Dₓ = 1.650 g cm⁻³, μ = 0.831 mm⁻¹. 30,389 reflections were measured up to a resolution of (sin θ/λ)max = 0.59 Å⁻¹. 4661 Reflections were unique (Rint = 0.0771), of which 3905 were observed (I > 2σ(I)). 346 Parameters were refined with 334 restraints (RIGU). R₁/wR₁[I > 2σ(I)] = 0.0382/0.0948. R₁/wR₁[all refl.]: 0.0510/0.1062. S = 1.038. CCDC 1423805.

X-ray crystal structure details of complex E

[C₅H₇N₂]_{2}OPRh PF₆, Fw = 590.29, yellow-brown block, 0.886 × 0.217 × 0.126 mm³, monoclinic, P2₁/n, a = 13.4021(9), b = 10.9937(7), c = 15.6906(10) Å, β = 97.462(3)°, V = 2292.3(3) Å³, Z = 4, Dₓ = 1.710 g cm⁻³, μ = 0.949 mm⁻¹. 97,401 reflections were measured up to a resolution of (sin θ/λ)max = 0.91 Å⁻¹. 14,600 reflections were unique (Rint = 0.0669), of which 10,763 were observed (I > 2σ(I)). 297 Parameters were refined with 279 restraints (RIGU). R₁/wR₁[I > 2σ(I)] = 0.0381/0.0833. R₁/wR₁[all refl.]: 0.0675/0.0988. S = 1.075. CCDC 1423806.

CCDC 1424620, 1423805 and 1423806 contain the supplementary crystallographic data for compounds A, B and E, respectively.
Details of the DFT calculations

Geometry optimizations were carried out with the Turbomole program package\textsuperscript{52} coupled to the PQS Baker optimizer\textsuperscript{53} via the BOpt package,\textsuperscript{54} at the ri-DFT level using the BP86\textsuperscript{55} functional and the resolution-of-identity (ri) method.\textsuperscript{56} The geometries of all stationary points were optimized at the def2-TZVP basis set level,\textsuperscript{57} both with and without Grimme’s dispersion corrections (disp3 version).\textsuperscript{58} 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. The relative (free) energies obtained from these calculations are reported in Scheme 7.

Acknowledgements

This research was funded by the Netherlands Organization for Scientific Research, section Chemical Sciences (NWO-CW; ECHO grant to BdB). JvIdV thanks the ERC for a Starting Grant (279097, EuReCat). The ApexII diffractometer at Utrecht University has been financed by NWO-CW. We thank Ed Zuidinga for performing the ESI-MS measurements.

Notes and references

1 (a) H. Staudinger, Ber. Dtsch. Chem. Ges., 1905, 38, 1733; (b) T. T. Sidwell, Eur. J. Org. Chem., 2006, 563; (c) D. H. Paull, A. Weatherx and T. Lectka, Tetrahedron, 2009, 65, 6771.

2 (a) A. D. Allen and T. T. Sidwell, Eur. J. Org. Chem., 2012, 1081; (b) A. D. Allen and T. T. Sidwell, Chem. Rev., 2013, 113, 7287.

3 (a) H. Staudinger and J. Meyer, Chem. Ber., 1920, 53, 72; (b) H. Perst, in Science of Synthesis, ed. R. L. Danheiser, Product Class 17: Ketenimines, 781, Georg Thieme Verlag, Stuttgart, 2006, vol. 23; (c) S. H. Kim, S. H. Park, J. H. Choi and S. Chang, Chem. – Asian J., 2011, 6, 2618; (d) S. E. Denmark and T. W. Wilson, Angew. Chem., Int. Ed., 2012, 51, 9980; (e) P. Lu and Y. Wang, Chem. Soc. Rev., 2012, 41, 5687; (f) C. Fromont and S. Masson, Tetrahedron, 1999, 55, 5405; (g) G. A. Gornowicz and R. West, J. Am. Chem. Soc., 1971, 93, 1714; (h) I. Bae, H. Han and S. Chang, J. Am. Chem. Soc., 2005, 127, 2038.

4 H. W. Moore and D. S. Wilbur, J. Org. Chem., 1980, 45, 4483.

5 (a) Y. Chiang, A. J. Kresge and V. V. Popik, J. Am. Chem. Soc., 1999, 121, 5930; (b) B. D. Wagner, B. R. Arnold, G. S. Brown and J. Lusztyk, J. Am. Chem. Soc., 1998, 120, 1827.

6 L. S. Hegedus, J. Montgomery, Y. Narukawa and D. C. Snustad, J. Am. Chem. Soc., 1991, 113, 5784.

7 Y. Yang, W. Shou, D. Hong and Y. Wang, J. Org. Chem., 2008, 73, 3574.

8 (a) G. A. Gornowicz and R. West, J. Am. Chem. Soc., 1971, 93, 1714; (b) M. Bendikov, H. M. Duong, E. Bolanos and F. Wudl, Org. Lett., 2005, 7, 783; (c) Y. Zhang, K. A. DeKorver, A. G. Lohse, Y. Zhang, J. Huang and R. P. Hsung, Org. Lett., 2009, 11, 899; (d) K. A. DeKorver, X. N. Wang, M. C. Walton and R. P. Hsung, Org. Lett., 2012, 14, 1768.

9 (a) M. P. Cassidy, J. Raushel and V. V. Fokin, Angew. Chem., Int. Ed., 2006, 45, 3154; (b) M. Whiting and V. V. Fokin, Angew. Chem., Int. Ed., 2006, 45, 3157.

10 (a) N. Ungvári and F. Ungváry, Carbonylation of diazoalkanes, in Modern Carbonylation Methods, ed. L. Kollár, Wiley-VCH, Weinheim, 2008, ch. 8, p. 199; (b) K. H. Dötz and J. Stendel, Chem. Rev., 2009, 109, 3227.

11 H. Staudinger and O. Kupfer, Ber. Dtsch. Chem. Ges., 1912, 45, 501.

12 (a) K. H. Dötz and J. Mühlmeier, Angew. Chem., Int. Ed. Engl., 1982, 21, 929; (b) P. T. Barger, B. D. Santarsiero, J. Armantrout and J. E. Bercaw, J. Am. Chem. Soc., 1984, 106, 5178–5186; (c) N. Ungvári, E. Fördös, J. Balogh, T. Kégl, L. Párkányi and F. Ungváry, Organometallics, 2010, 29, 3837.

13 TM-catalysed carbonylation of dihalides: (a) A. Miyashita, T. Kihara, K. Nomura and H. Nohira, Chem. Lett., 1986, 1607; (b) M. Huser, M. Youinou and J. A. Osborn, Angew. Chem., Int. Ed. Engl., 1989, 28, 1386.

14 TM-catalysed carbonylation of diazo compounds: (a) T. Ye and M. A. Mckervey, Chem. Rev., 1994, 94, 1091; (b) R. Tuba and F. Ungváry, J. Mol. Catal. A: Chem., 2003, 203, 59; (c) Z. Zhang and J. Wang, Tetrahedron, 2008, 64, 6577; (d) E. Fördös, R. Tuba, L. Párkányi, T. Kégl and F. Ungváry, Eur. J. Org. Chem., 2009, 1994; (e) Z. Zhang, Y. Liu, L. Ling, Y. Li, Y. Dong, M. Gong, X. Zhao, Y. Zhang and J. Wang, J. Am. Chem. Soc., 2011, 133, 4330; (f) N. D. Paul, A. Chirila, H. Lu, X. P. Zhang and B. Bruin, Chem. – Eur. J., 2013, 19, 12953; (g) Z. Zhang, Y. Zhang and J. Wang, ACS Catal., 2011, 1, 1621; (h) Q. Xiao, Y. Zhang and J. Wang, Acc. Chem. Res., 2013, 46, 236.

15 J. R. Fulton, V. K. Aggarwal and J. De Vicente, Eur. J. Org. Chem., 2005, 1479.

16 C. R. Pitts and T. Lectka, Chem. Rev., 2014, 114, 7930.

17 (a) J. A. Green and L. A. Singer, Tetrahedron Lett., 1969, 5093; (b) T. W. Hudnall, E. J. Moorhead, D. G. Gusev and C. W. Bielawski, J. Org. Chem., 2010, 75, 2763; (c) G. A. Blake, J. P. Moerdyk and C. W. Bielawski, Organometallics, 2012, 31, 3373; (d) D. Martin, Y. Canac, V. Lalavo and G. Bertrand, J. Am. Chem. Soc., 2014, 136, 5023.

18 (a) F. Zhou, K. Ding and Q. Cai, Chem. – Eur. J., 2011, 17, 12268; (b) Q. Dai, Y. Jiang, J-T. Yu and J. Cheng, Chem. Commun., 2015, DOI: 10.1039/c5cc06771e.

19 R. Lindner, B. van den Bosch, M. Lutz, J. N. H. Reek and J. I. van der Vlugt, Organometallics, 2011, 30, 499.

20 (a) E. Fogler, J. A. Garg, P. Hu, G. Leitus, L. J. W. Shimom and D. Milstein, Chem. – Eur. J., 2014, 20, 15727.
27 Alternatively, 7a could be formed by direct coupling of the metallocarbene intermediate II and the aniline nucleophile, followed by a parallel dehydrogenation process. However, no dehydrogenation or transfer hydrogenation of benzylamine was observed when using B or E as the catalyst under similar conditions, indicating a fast dehydrogenation process of a metal-bound amine/amido intermediate following the undesired C—N coupling, if that is the case. 

28 (a) R. B. Morin and M. Gorman, *Chemistry and Biology of β-Lactam Antibiotics*, Academic Press, New York, 6th edn, 1982; (b) B. Alcaide, P. Almendros and C. Aragoncillo, *Chem. Rev.*, 2007, 107, 4437; (c) T. T. Tidwell, *Angew. Chem., Int. Ed.*, 2008, 47, 1016; (d) N. A. A. El-Kanzi, *Heterocycl. Lett.*, 2013, 3, 81; (e) A. Gupta and A. K. Halve, *Int. J. Pharm. Sci. Res.*, 2015, 6, 978.

29 (a) M. Staudinger, *Justus Liebig’s Ann. Chem.*, 1907, 356, 51; (b) G. I. Georg and V. T. Ravikumar, in *The Organic Chemistry of β-Lactams*, ed. G. I. Georg, Verlag Chemie, New York, 1993, p. 295; (c) C. Palomo, J. M. Aizpurua, I. Ganboa and M. Oiarbide, *Curr. Med. Chem.*, 2004, 11, 1837; (d) R. Tuba, *Org. Biomol. Chem.*, 2013, 11, 5976.

30 (a) L. S. Hegedus, J. Montgomery, Y. Narukawa and D. C. Snustad, *J. Am. Chem. Soc.*, 1991, 113, 5784; (b) S. France, A. Weatherwax, A. E. Taggi and T. Lectka, *Acc. Chem. Res.*, 2004, 37, 592; (c) Y. Wang, Y. Liang, L. Jiao, D. M. Du and J. Xu, *J. Org. Chem.*, 2006, 71, 6983; (d) B. K. Banik, B. Lecea, A. Arrieta, A. de Cözar and F. P. Cossio, *Angew. Chem., Int. Ed.*, 2007, 46, 3028; (e) F. P. Cossio, A. Arrieta and M. A. Sierra, *Acc. Chem. Res.*, 2008, 41, 925; (f) H. Qi, X. Li and J. Xu, *Org. Biomol. Chem.*, 2011, 9, 2702.

31 R. Tuba, *Org. Biomol. Chem.*, 2013, 11, 5976.

32 (a) M. C. Pirrung, H. Liu and A. T. Morehead Jr., *J. Am. Chem. Soc.*, 2002, 124, 1014; (b) F. M. Wong, J. Wang, A. C. Hengge and W. Wu, *Org. Lett.*, 2007, 9, 1663.

33 (a) E. Nakamura, N. Yoshikai and M. Yamanaka, *J. Am. Chem. Soc.*, 2002, 124, 7181; (b) J. Hansen, J. Autschbach and H. M. L. Davies, *J. Org. Chem.*, 2009, 74, 6555; (c) N. D. Paul, S. Mandal, M. Otte, X. Cui, X. P. Zhang and B. de Bruin, *J. Am. Chem. Soc.*, 2014, 136, 1090; (d) W. I. Dzik, X. Xu, X. P. Zhang, J. N. H. Reek and B. de Bruin, *J. Am. Chem. Soc.*, 2010, 132, 10891; (e) A. J. C. Walters, J. N. H. Reek and B. de Bruin, *ACS Catal.*, 2014, 4, 1376.

34 (a) T. Schwabe and S. Grimm, *Phys. Chem. Chem. Phys.*, 2007, 9, 3397; (b) K. E. Riley and M. Piton, *Chem. Rev.*, 2010, 110, 5023; (c) J. P. P. Ramalho, J. R. B. Gomes and F. Illas, *RSC Adv.*, 2013, 3, 13085.

35 (a) R. G. Pearson, *J. Am. Chem. Soc.*, 1963, 85, 3533; (b) R. G. Pearson, *Science*, 1966, 151, 172; (c) R. G. Pearson, *Chemical Hardness - Applications From Molecules to Solids*, Wiley-VCH, Weinheim, 1997.

36 (a) H. Werner and E. Bleuel, *Angew. Chem., Int. Ed.*, 2001, 40, 145; (b) D. B. Grojahn, L. S. B. Collins, M. Wolpert, G. a. Blizhanova, H. C. Lo, D. Combs and J. L. Hubbard, *J. Am. Chem. Soc.*, 2001, 123, 8260.

37 The direct uncatalysed concerted (but non-synchronous) \([2 + 2]\) cycloaddition reaction of the \(\text{trans-}^{\text{imm}}\text{MeC}={\text{NMe}}\) ketene OC—=CHCOOMe in the gas phase was considered, without any proton- or Lewis-acid-assistance (i.e. not acid-catalysed). This barrier seems most relevant for comparison with the Rh-catalysed pathways considering the fact that the experimental reactions were performed under basic reaction conditions.

38 Rather high reaction barriers were also obtained in other studies of \([2 + 2]\) cyclo-addition reactions involving several differently substituted ketenes and imines and using various computational models: (a) B. K. Banik, B. Lecea, A. Arrieta, A. de Cözar and F. P. Cossio, *Angew. Chem., Int. Ed.*, 2007, 46, 3028; (b) N. Fu and T. T. Tidwell, *Tetrahedron*, 2008, 64, 10465; (c) C. Zhou, *Studies on cycloaddition reactions of ketenes: further investigations of pseudopericyclic reaction mechanisms*, PhD Thesis, Texas Tech University, 2004, http://hdl.handle.net/2346/10697.

39 L. S. Jongbloed, B. de Bruin, J. N. H. Reek, M. Lutz and J. I. van der Vlugt, *Chem. – Eur. J.*, 2015, 21, 7297.

40 M. Seitz, A. Kaiser, A. Tereshchenko, C. Geiger, Y. Uematsu and O. Reiser, *Tetrahedron*, 2006, 62, 9973.

41 G. J. P. Britovsek, J. England and A. J. P. White, *Dalton Trans.*, 2006, 1399.

42 M. Gargir, Y. Ben-David, G. Leitus, Y. Diskin-Posner, L. J. W. Shimon and D. Milstein, *Organometallics*, 2012, 31, 6207.

43 J. R. Fulton, V. K. Aggarwal and J. de Vicente, *Eur. J. Org. Chem.*, 2005, 1479.

44 (a) P. Doppelt, J. Fischer and R. Webs, *Inorg. Chem.*, 1984, 23, 2958–2962; (b) R. L. Halterman and S. T. Jan, *J. Org. Chem.*, 1991, 56, 5253; (c) X. Xu, H. Lu, J. V. Ruppel, X. Cui,
S. L. de Mesa, L. Wojtas and X. P. Zhang, *J. Am. Chem. Soc.*, 2011, 133, 15292.

45 A. M. M. Schreurs, X. Xian and L. M. J. Kroon-Batenburg, *J. Appl. Crystallogr.*, 2010, 43, 70.

46 G. M. Sheldrick, SADABS, Universität Göttingen, Germany, 2008.

47 G. M. Sheldrick, *Acta Crystallogr., Sect. A: Fundam. Crystallogr.*, 2015, 71, 3.

48 G. M. Sheldrick, *Acta Crystallogr., Sect. A: Fundam. Crystallogr.*, 2008, 64, 112.

49 A. L. Spek, *Acta Crystallogr., Sect. D: Biol. Crystallogr.*, 2009, 65, 148.

50 Bruker, APEX2 software, Madison WI, USA, 2014.

51 G. M. Sheldrick, SHELXL2013, University of Göttingen, Germany, 2013.

52 R. Ahlrichs, *Turbomole Version 6.5*, Theoretical Chemistry Group, University of Karlsruhe.

53 PQS version 2.4, Parallel Quantum Solutions, Fayetteville, Arkansas, USA, 2001; the Baker optimizer is available separately from PQS upon request: I. Baker, *J. Comput. Chem.*, 1986, 7, 385.

54 P. H. M. Budzelaar, *J. Comput. Chem.*, 2007, 28, 2226.

55 (a) A. D. Becke, *Phys. Rev. A*, 1988, 38, 3098; (b) J. P. Perdew, *Phys. Rev. B: Condens. Matter*, 1986, 33, 8822.

56 M. Sierka, A. Hogekamp and R. Ahlrichs, *J. Chem. Phys.*, 2003, 118, 9136.

57 A. Schaefer, H. Horn and R. Ahlrichs, *J. Chem. Phys.*, 1992, 97, 2571.

58 S. Grimme, J. Antony, S. Ehrlich and H. Krieg, *J. Chem. Phys.*, 2010, 132, 154.