

Metal–metal multiple bonded intermediates in catalysis

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Abstract. Metal–metal bonded Rh_2 and Ru_2 complexes having a paddlewheel-type structure are exceptional catalysts for a broad range of organic transformations. I review here the recent efforts towards the observation and characterization of intermediates in these reactions that have previously eluded detection. Specifically, mechanistic investigations of carbenoid and nitrenoid reactions of $Rh_2(II,II)$ -tetracarboxylate compounds have led to the observation of a metastable $Rh_2(II,II)$ carbene complex as well as a mixed-valent $Rh_2(II,III)$ -amido intermediate. Related Ru_2 nitrido compounds have been studied and found to undergo intramolecular C–H amination reactions as well as intermolecular reaction with triphenylphosphine.

Keywords. Catalysis; metal-metal bonds; carbene; nitrene; nitride.

1. Introduction

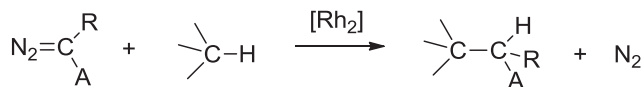
Since the recognition of the first metal–metal quadruple bond 50 years ago,¹ metal–metal bonded paddlewheel-type complexes have been extensively studied with respect to their structural, spectral, redox and chemical properties.² One of the foremost applications of these compounds is in the area of catalysis, where dirhodium tetracarboxylate compounds in particular, have been shown to catalyse a wide number of carbene- and nitrene-transfer reactions. The most spectacular of these catalytic reactions involve the insertion of a carbene or nitrene into unactivated C–H bonds (scheme 1).^{3–9} These catalytic reactions are presumed to occur via the intermediacy of discrete Rh_2 -carbene or Rh_2 -nitrene complexes that feature a proposed linear $Rh-Rh=E$ unit, where E = the carbene or nitrene fragment. Studies aimed at elucidating the mechanism of these reactions with special emphasis on the detection and spectroscopic characterization of the proposed $Rh-Rh=E$ species, are reviewed here. The efforts to characterize related $Ru-Ru\equiv N$ nitrido compounds are also discussed.

2. Rh_2 carbene chemistry

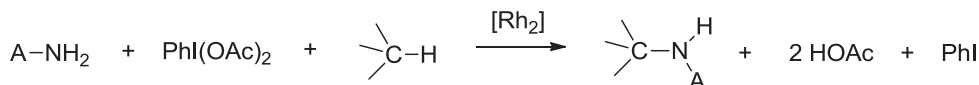
Early studies of Rh_2 -catalysed carbenoid reactions led to the postulation of a discrete Rh_2 -carbene complex as an intermediate in the reaction, primarily on the basis of reaction selectivity.^{10–12} An illuminating study reported in 1984 by Doyle and co-workers showed a strong correlation between reaction products of Rh_2 -catalysed

reactions and those obtained from stoichiometric reactions of an isolated W-carbene complex,¹³ thus strongly implicating an Rh_2 carbene complex as an intermediate. Computational studies have also been highly informative and suggest a linear $Rh-Rh=CR_2$ geometry for the postulated carbene intermediate.^{14–18} The calculated electronic structure of this intermediate has been extensively described by Nakamura and co-workers¹⁶ and was further refined by Berry.¹⁹ The key electronic feature of this intermediate is delocalized $Rh-Rh-C$ three-centre bonding with appropriate three-centre orbitals of σ and π symmetry. The resulting $Rh-Rh-C$ three-centre/four-electron bonds of σ and π symmetry lead to a description of the $Rh=C$ bond as being weak with only partial σ character and partial π character, and the $Rh=C$ bond is calculated to have an overall bond order of ~ 0.7 – 0.8 . Notably, the LUMO of the carbene complex has a significant degree of empty p orbital character on the C atom, providing a strong rationale for its highly electrophilic reactivity.

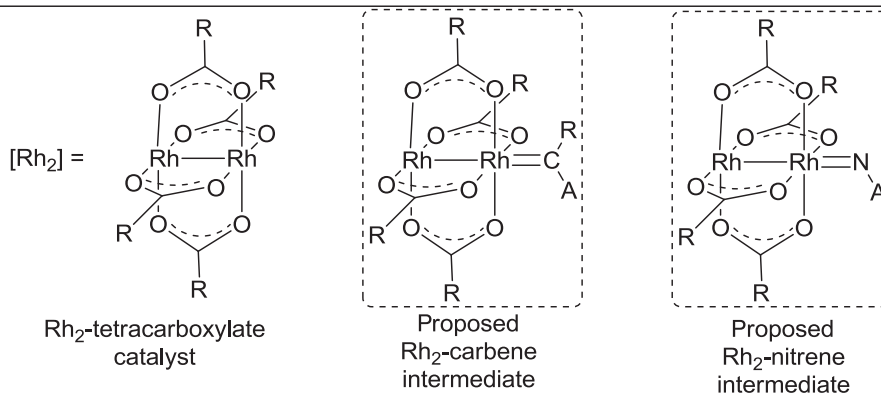
An important issue that has been investigated both experimentally and computationally is the nature and effect of the substituents on the carbene C centre. Organic diazo compounds are almost exclusively used as carbene precursors in Rh_2 -catalysed reactions, and three general classes of these compounds have been studied (scheme 2).^{4,20} Diazo compounds bearing two electron accepting groups (A/A compounds, in which the A groups are typically esters) are quite stable and may require forcing conditions to react with the Rh_2 catalyst. The carbenes derived from A/A diazo compounds

Carbenoid C–H functionalization

R = Ar, H
A = COOCH₃

Nitrenoid C–H amination

A = SO₃R, COOR



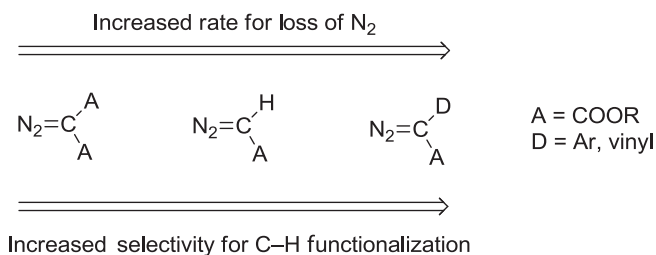
Scheme 1. Overview of Rh₂-catalysed C–H functionalization chemistry.

are highly reactive and react indiscriminately with C–H bonds, even in the presence of Rh₂ catalysts. The most widely used diazo compounds are those with only one acceptor group (A-only; e.g., the commercially available ethyl diazoacetate). For these species, loss of N₂ is still the most important, and rate-limiting, reaction step. Diazo compounds that bear both an electron acceptor group and an electron donor group (D/A compounds) have a number of appealing properties. Loss of N₂ from these species is more readily achieved. Also, the carbene formed from these species is stabilized by the presence of the electron donor group and is therefore not as reactive as the A-only or A/A species. Thus, C–H functionalization from a D/A carbene is, in general, more selective than with other carbene precursors.

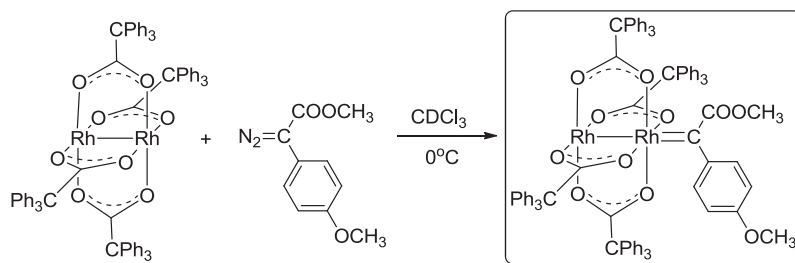
Using such D/A precursors, elegant means of controlling the regio- and stereoselectivity of these reactions have been developed.^{4,6,20}

The reaction coordinate for the loss of N₂ and functionalization of cyclopentane has been evaluated computationally for ethyl diazoacetate (A-only) as well as ethyl phenyldiazoacetate (D/A).¹⁸ The major calculated difference in these reactions is that the carbene intermediate was found to be significantly more stable for D/A substrate than for the A-only substrate, in the order of ~40 kJ/mol.¹⁸ This result suggested that a Rh₂-D/A carbene complex might be stable enough to be observed.

Indeed, the combination of the very bulky Rh₂ tetrakis(triphenylcarboxylate) (Rh₂(TPA)₄) complex with the D/A diazo compound methyl 4-methoxyphenyldiazoacetate led to the observation of a deep blue metastable species that is stable for ~20 h at 0°C in chlorinated (and deuterated) solvents (scheme 3).²¹ The identity of this intermediate as the first observed metastable Rh₂ carbene complex was confirmed by a suite of spectroscopic methods. ¹³C NMR spectroscopy and resonance Raman spectroscopy were used to establish the Rh=C linkage, while EXAFS analysis allowed for a determination of the Rh–Rh bond length of 2.43 Å.²¹ Results from DFT calculations were in agreement with all



Scheme 2. Trends in reactivity for the different classes of organic diazo compounds.



Scheme 3. Preparation of the first Rh₂ D/A carbene complex.

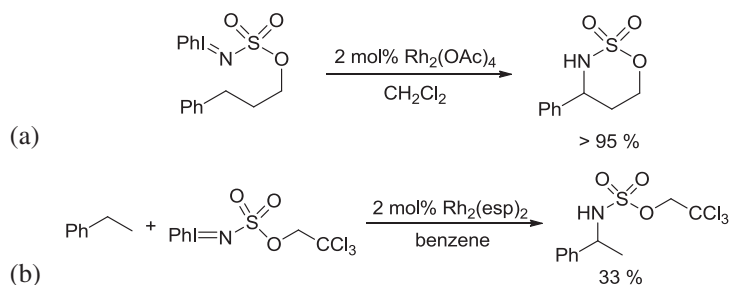
the spectroscopic observables, and the reactivity of the intermediate was found to be consistent with catalytic reactions involving Rh₂(TPA)₄. Specifically, cyclopropanation of styrene and insertion into the C–H bond of tetrahydrofuran were observed.²¹

3. Rh₂ nitrene chemistry

Rh₂-catalysed nitrenoid chemistry is mechanistically more complex than the corresponding carbenoid chemistry. This is mainly because an external oxidant, typically a hypervalent organoiodine reagent, is utilized to generate the nitrene species *in situ*.⁸ Mechanistic studies by the Du Bois lab have uncovered a number of critical observations. First, kinetic analysis indicated that the rate-limiting step is a likely reaction of the nitrogen substrate with the oxidant to form an iminoiodinane species,^{22,23} which is envisioned to react in a subsequent step with the Rh₂ catalyst to form an Rh₂ nitrene complex. Several proposed intermediates for these reactions have been implicated as being catalytically relevant on the basis of signals observed in mass spectra taken *in situ*.²⁴ A growing amount of experimental evidence suggests that these reactions are even more complex than what would be expected from a simple nitrene interception/insertion mechanism. For example, there are distinct mechanistic differences for C–H amination depending on whether the reaction is intramolecular or intermolecular. The data in scheme 4 provide a poignant example. These reactions on isolated iminoiodinane compounds were performed as a

test of the competence of the proposed iminoiodinane intermediates.^{22,23} For the intramolecular cyclization in scheme 4a, the yield of the product is comparable to that of a catalytic reaction in which the iminoiodinane is formed *in situ*. However, an analogous intermolecular reaction, scheme 4b, produces the C–H amination product in significantly lower yield (33%) than under *in situ* conditions (~70%), suggesting that there may be an alternative catalytic mechanism that bypasses iminoiodinane intermediates. Another intriguing difference between intra- and intermolecular reactions is that the reaction mixture turns a persistent red colour in the latter case but only sometimes in the former.^{23,25} This red colour has been attributed to a one-electron oxidized form of the catalyst, either [Rh₂(esp)₂]⁺ or Rh₂(esp)₂Cl, from which it was hypothesized that catalyst degradation occurs readily (here, esp = α, α', α', α'-tetramethyl-1,3-benzenedipropanoate).^{23,25}

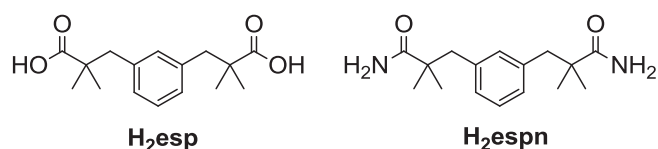
My lab recently reported further, direct evidence of multiple mechanistic pathways for intermolecular C–H amination. For the intermolecular C–H amination reaction of ethylbenzene with H₂NTces (Tces = trichloroethylsulphonate) in the presence of PhI(OAc)₂, a plot of product concentration vs. time shows that product formation occurs quickly in an initial burst of reactivity in the first 5–10 min, but continues after this initial burst to produce a significant amount of further product at a slower rate.²⁶ In efforts to explain this unusual reactivity as well as to elucidate the role of putative one-electron oxidized Rh₂(II,III) species that had been observed during the course of the reaction, bulk coulometric oxidation of the Rh₂(esp)₂ catalyst



Scheme 4. Reactions using pre-formed iminoiodinane compounds.

was explored. This experiment led to the identification of a one-electron oxidized $\text{Rh}_2(\text{II,III})$ -amido species, $\text{Rh}_2(\text{esp})_2(\text{HNTces})$ (**A** in scheme 5), which matched the spectroscopic features observed during catalysis.²⁶ **A** was found to be competent for C–H amination since it reacts with $\text{PhI}(\text{OAc})_2$ in the presence of substrate to regenerate the $\text{Rh}_2(\text{esp})_2$ catalyst in its unoxidized form. From these data, the double catalytic cycle for C–H amination shown in scheme 5 was proposed.²⁶ The inner reaction cycle is essentially the same as that proposed by Du Bois involving group transfer from iminoiodinane species, whereas the outer cycle relies on proton-coupled electron transfer steps to avoid the formation of an iminoiodinane species. The inner cycle is likely responsible for the fast initial burst of reactivity, and the outer reaction cycle appears to be the slower reaction that dominates product formation at longer reaction times.²⁶

Interestingly, when the esp ligand is exchanged for structurally analogous ligands that are redox non-innocent, only ligand-centred oxidation chemistry is observed.²⁷ The Rh_2 complexes bearing redox non-innocent ligands are only able to perform the initial burst of reactivity observed for $\text{Rh}_2(\text{esp})_2$ and then cease to function. Thus, these catalysts appear to only be capable of catalysis via the inner nitrene interception/insertion cycle of scheme 5 and cannot use the outer single-electron cycle of scheme 5.²⁷ These results highlight the necessity for metal-centred redox capability in intermolecular C–H amination. In this case, ligand-centred redox chemistry does not substitute for metal-centred redox chemistry, and the electronic structure of the $\text{Rh}_2(\text{II,III})$ state appears to be suitable for carrying out C–H amination. To test this idea,

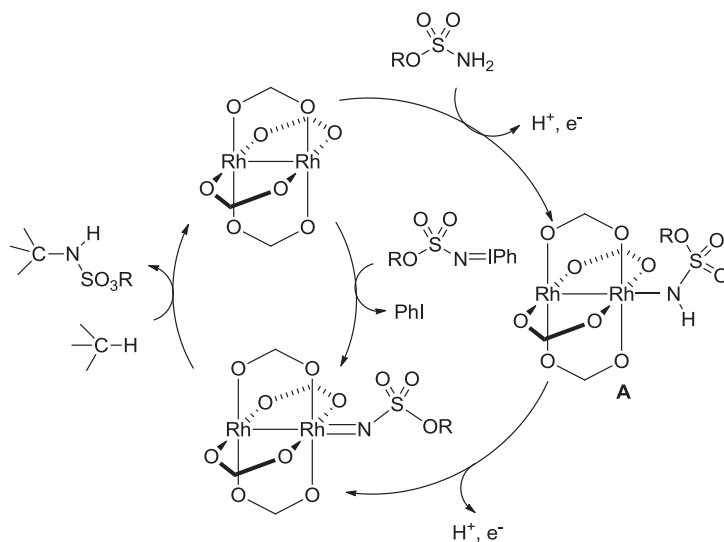


Scheme 6. Structures of the esp and espn ligands.

the deliberate preparation of stable $\text{Rh}_2(\text{II,III})$ complexes has been pursued so that their performance in C–H amination catalysis could be evaluated. As amply demonstrated by Doyle,²⁸ it is possible to stabilize the $\text{Rh}_2(\text{II,III})$ oxidation state by using carboxamidate equatorial ligands rather than carboxylates. Thus, the redox chemistry of $\text{Rh}_2(\text{espn})_2$ was explored, in which the new ligand espn is the carboxamidate version of esp (scheme 6).²⁹ The $\text{Rh}_2(\text{II,III})$ species $\text{Rh}_2(\text{espn})_2\text{Cl}$ is stable and was isolated as two isomers, both of which perform exceptionally well as catalysts for intramolecular C–H amination.²⁹ Owing to the expense and rarity of Rh, lowering the catalyst loading required for C–H amination is a major goal. With the $\text{Rh}_2(\text{espn})_2\text{Cl}$ catalyst, a maximum turnover number of 1400 at a catalyst loading of 0.05 mol% was achieved,²⁹ which is, to our knowledge, the highest turnover number yet reported for Rh_2 -catalysed C–H amination.

4. Ru_2 Nitrido chemistry

Noting that multiple-bonded Rh-Rh=E structures with $\text{E} = \text{CR}_2$ or NR are proposed as key intermediates in Rh_2 -catalysed carbenoid and nitrenoid reactions, respectively, it seemed likely that exploration of related



Scheme 5. Proposed mechanism for intermolecular C–H amination. Organic groups on the catalyst are removed for clarity.

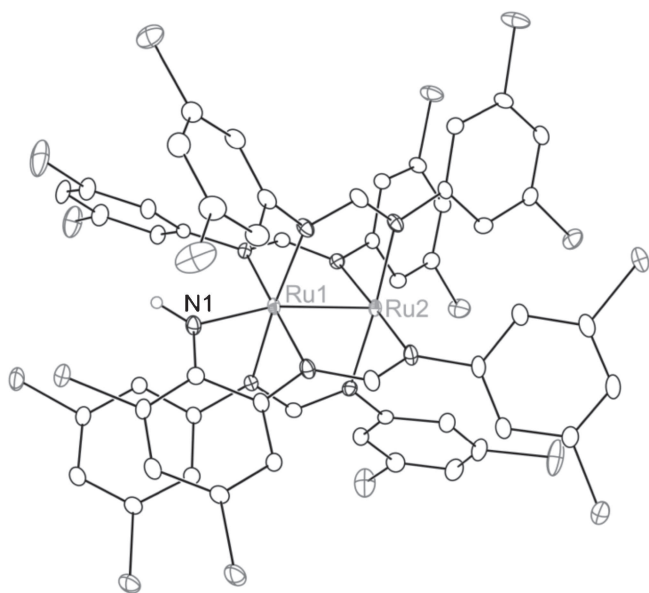


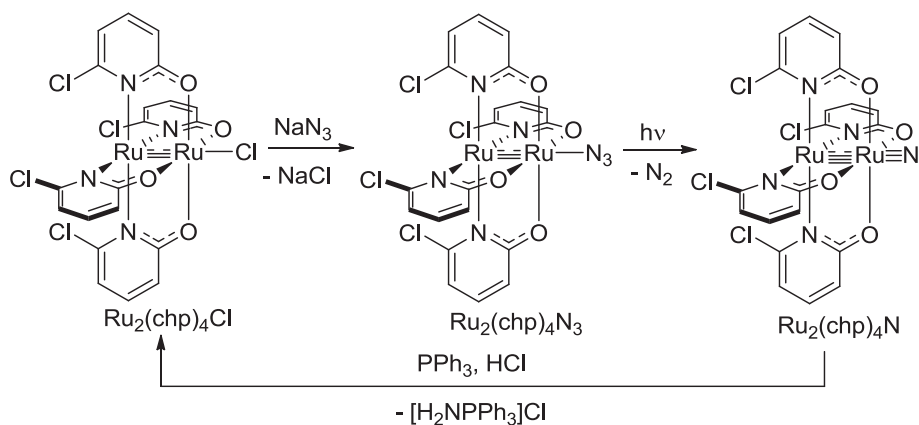
Figure 1. Crystal structure of $\text{Ru}_2[(\text{D}(3,5\text{-Cl}_2)\text{PhF})_3(\text{D}(3,5\text{-Cl}_2\text{-2-NH})\text{PhF})]$.

M-M=E structures might be a fruitful avenue for the discovery of new reactivity. The first such complexes to be generated and characterized were Ru_2 nitrido complexes having a linear $\text{Ru-Ru}\equiv\text{N}$ structure.³⁰

A number of Ru_2 complexes bearing axial azide ligands were reported in 2005,³¹ which, in principle, could serve as precursors for Ru_2 -nitrido compounds. The first Ru_2 nitrido compound, $\text{Ru}_2(\text{DPhF})_4\text{N}$ ($\text{DPhF} = \text{N,N}'\text{-diphenylformamidinate}$), originally prepared by cryogenic photolysis of the corresponding azido complex,³⁰ was found to be thermally unstable. In an effort to understand the nature of this instability, the related $\text{Ru}_2(\text{D}(3,5\text{-Cl}_2)\text{PhF})_4\text{N}_3$ azide complex was investigated, in which the supporting ligands have chloro substituents at the 3,5 positions of all the aryl rings. Using this azide complex, it was possible to expel

N_2 cleanly via thermolysis rather than photolysis.³² The stable product obtained after thermolysis was not the nitrido complex; it was instead the compound shown in figure 1 in which the N atom of a putative Ru_2 nitride inserted into an aryl C–H bond of one of the $\text{D}(3,5\text{-Cl}_2)\text{PhF}$ ligands.³² A nitride intermediate was implicated in this study by the fact that differential scanning calorimetry (DSC) of the Ru_2 -azide precursor showed two distinct features, each associated with an exothermic chemical transformation. This result is consistent with a mechanism involving two steps: exothermic loss of N_2 from the azide group to form a nitrido intermediate, followed by exothermic insertion of the nitride into the ligand C–H bond.³² In further support of this general mechanism, an analogous C–H insertion product was obtained upon thawing out a frozen solution of the original $\text{Ru}_2(\text{DPhF})_4\text{N}$ nitrido complex.³²

Computational results on the Ru_2 nitrido system indicated that the C–H amination reaction follows an electrophilic aromatic substitution mechanism in which the nitride N atom is the electrophile.³³ The nitrido N atom is rendered electrophilic via the same three-centre/four-electron bonding manifold that is operative in the Rh_2 -carbene and Rh_2 -nitrene intermediates.¹⁹ Further computational study has explored the energetics of the electrophilic aromatic substitution mechanism using a series of hypothetical $\text{M-Ru}\equiv\text{N}$ and $\text{M-Mo}\equiv\text{N}$ compounds as well as mononuclear $\text{Ru}\equiv\text{N}$ and $\text{Mo}\equiv\text{N}$ models, in order to determine the role of the metal–metal bond in C–H amination reactivity.³⁴ Through analysis of all the energetics of these reactions, two generalizations were made. First, transition state energies were uniformly higher in energy for mononuclear $\text{M}\equiv\text{N}$ compounds than they were for binuclear metal–metal bonded M_2 nitrido compounds, signifying that the $\text{M-M}\equiv\text{N}$ electronic structure greatly facilitates C–H amination via the electrophilic aromatic substitution



Scheme 7. Synthetic cycle for N-atom transfer using the $\text{Ru}_2(\text{chp})_4$ core.

pathway. Secondly, transition state energies were uniformly higher for M–Mo≡N compounds than they were for M–Ru≡N compounds, consistent with greater electrophilicity of the latter species.³⁴

In order to disfavour intramolecular reactions, a new Ru₂-nitride precursor was designed that utilizes the Ru₂(chp)₄ core (chp = 6-chlorohydroxypyridinate). The compound Ru₂(chp)₄Cl was reported in 1985 by Chakravarty *et al.*³⁵ and its structure was found to have a '4.0' configuration in which all the O atoms bind to one Ru atom and all the N atoms bind to the other Ru atom as indicated in scheme 7. Replacement of the axial chloro ligand for azide produces Ru₂(chp)₄N₃, which retains the '4.0' configuration and can therefore be used to produce a Ru₂ nitrido species having no prospect for intramolecular reactivity.³⁶ The Ru₂(chp)₄N nitrido complex, formed upon photolysis, is easily trapped by an intermolecular reaction with PPh₃, from which the [H₂NPPH₃]⁺ ion can be obtained after acidic workup.³⁶ Remarkably, the Ru₂(chp)₄ core is resistant to the acidic conditions, and Ru₂(chp)₄Cl can be regenerated to close a cycle for intermolecular N atom transfer.³⁶

5. Summary

Efforts to identify reactive metal–metal bonded complexes having a linear M–M=E structure have led to the observation of important intermediates in Rh₂-catalysed carbenoid and nitrenoid transformations. Inspired by the structures of these intermediates, we have been able to explore novel reactivity of the Ru–Ru≡N core including intramolecular C–H amination as well as intermolecular N atom transfer.

Acknowledgements

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References

- Cotton F A, Curtis N F, Harris C B, Johnson B F G, Lippard S J, Mague J T, Robinson W R and Wood J S 1964 *Science* **145** 1305
- Cotton F A, Murillo C A and Walton R A 2005 *Multiple bonds between metal atoms* (New York: Springer Science and Business Media, Inc.)
- Doyle M P and Forbes D C 1998 *Chem. Rev.* **98** 911
- Davies H M L and Beckwith R E J 2003 *Chem. Rev.* **103** 2861
- Davies H M L and Manning J R 2008 *Nature* **451** 417
- Doyle M P, Duffy R, Ratnikov M and Zhou L 2010 *Chem. Rev.* **110** 704
- Du Bois J 2011 *Org. Proc. Res. Dev.* **15** 758
- Roizen J L, Harvey M E and Du Bois J 2012 *Acc. Chem. Res.* **45** 911
- Kornecki K P, Powers D C, Ritter T and Berry J F 2014 In *Prog. Inorg. Chem.*, Karlin K D (ed.) (Hoboken: John Wiley & Sons, Inc.) p. 225
- Doyle M P, Westrum L J, Wolthuis W N E, See M M, Boone W P, Bagheri V and Pearson M M 1993 *J. Am. Chem. Soc.* **115** 958
- Padwa A, Austin D J, Price A T, Semones M A, Doyle M P, Protopopova M N, Winchester W R and Tran A 1993 *J. Am. Chem. Soc.* **115** 8669
- Doyle M P and Ren T 2001 *Prog. Inorg. Chem.* **49** 113
- Doyle M P, Griffin J H, Bagheri V and Dorow R L 1984 *Organometallics* **3** 53
- Sheehan S M, Padwa A and Snyder J P 1998 *Tetrahedron Lett.* **39** 949
- Padwa A, Snyder J P, Curtis E A, Sheehan S M, Worsencroft K J and Kappe C O 2000 *J. Am. Chem. Soc.* **122** 8155
- Nakamura E, Yoshikai N and Yamanaka M 2002 *J. Am. Chem. Soc.* **124** 7181
- Nowlan D T, Gregg T M, Davies H M L and Singleton D A 2003 *J. Am. Chem. Soc.* **125** 15902
- Hansen J, Autschbach J and Davies H M L 2009 *J. Org. Chem.* **74** 6555
- Berry J F 2012 *Dalton Trans.* **41** 700
- Davies H M L and Morton D 2011 *Chem. Soc. Rev.* **40** 1857
- Kornecki K P, Briones J F, Boyarskikh V, Fullilove F, Autschbach J, Schrote K E, Lancaster K M, Davies H M L and Berry J F 2013 *Science* **342** 351
- Fiori K W and Du Bois J 2007 *J. Am. Chem. Soc.* **129** 562
- Fiori K W, Espino C G, Brodsky B H and Du Bois J 2009 *Tetrahedron* **65** 3042
- Perry R H, Cahill T J, III, Roizen J L, Du Bois J and Zare R N 2012 *Proc. Nat. Acad. Sci. U.S.A.* **109** 18295
- Zalatan D N and Du Bois J 2009 *J. Am. Chem. Soc.* **131** 7558
- Kornecki K P and Berry J F 2011 *Chem. Eur. J.* **17** 5827
- Kornecki K P and Berry J F 2012 *Eur. J. Inorg. Chem.* 562
- Doyle M P 2006 *J. Org. Chem.* **71** 9253
- Kornecki K P and Berry J F 2012 *Chem. Commun.* **48** 12097
- Pap J S, George S D and Berry J F 2008 *Angew. Chem. Int. Ed.* **47** 10102
- Chen W Z, De Silva V, Lin C, Abellard J, Marcus D M and Ren T 2005 *J. Clust. Sci.* **16** 151
- Long A K M, Yu R P, Timmer G H and Berry J F 2010 *J. Am. Chem. Soc.* **132** 12228
- Long A K M, Timmer G H, Pap J S, Snyder J L, Yu R P and Berry J F 2011 *J. Am. Chem. Soc.* **133** 13138
- Timmer G H and Berry J F 2012 *Chem. Sci.* **3** 3038
- Chakravarty A R, Cotton F A and Tocher D A 1985 *Inorg. Chem.* **24** 1263
- Cocos A R, Long A K M, Guzei I A and Berry J F 2013 *Eur. J. Inorg. Chem.* **2013** 3808