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Cleavage of unreactive bonds with pincer metal complexes

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Since the first reports some three decades ago, the chemistry of pincer metal complexes has seen a tremendous development with impact on materials chemistry, supramolecular chemistry, bioorganometallics, and, presumably most significantly, on (catalytic) bond making and breaking processes. The remarkable progress is due to a large extent to the well-defined nature and tunability of the pincer ligand which allows the reactivity of the metal center to be modified and eventually tailored to specific needs. This *Perspective* summarizes the achievements in employing pincer complexes for mediating and catalyzing the cleavage of typically unreactive bonds such as C–H, C–C, C–E, and E–H bonds, arguably one of the most spectacular applications of pincer chemistry.

Introduction

Pincer ligands have become extraordinarily useful scaffolds for directing specific reactivity patterns of metal centers for a large variety of applications, for example as highly efficient sensors, switches, and catalysts.[1] Pincer ligands are typically characterized by a monoanionic *E,C,E*-terdentate bonding mode where C denotes a central carbanion, often an aryl anion, and E represents a neutral two-electron donor such as an amine, imine, phosphine, phosphinite, sulfide or selenide (Fig 1). In general, these ligands adopt a meridional coordination mode,[2] and as a consequence, the M–C bond in pincer complexes is effectively shielded and considerably stabilized as compared to other M–C bonds. As a consequence, the high *trans* effect of the anionic central ligand can be fully exploited in pincer complexes. Furthermore, the electron density at the coordinated metal center may be altered and eventually tailored by selective ligand modification, which does not affect the general bonding mode of the ligand, *e.g.* via introduction of electroactive groups on the aryl ring (R') or on the heteroatom E.

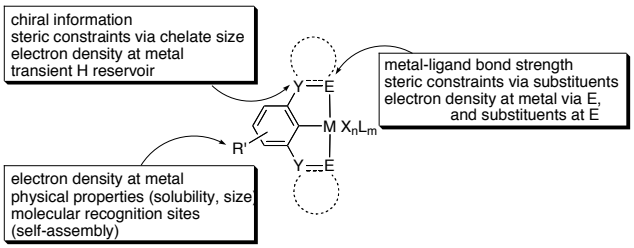


Fig. 1. General representation of an ECE pincer ligand coordinated to a metal fragment (MX_nL_m), including the different functions that can be regulated by appropriate ligand modifications.

Various modifications have been implemented on the general pincer scaffold, including the substitution of the central carbanion by an amide (NR_2^-) or a silyl anion.[3] Similarly, the linker between the core unit and the donor arms has been changed from an sp^2- or sp^3-hybridized carbon to oxygen. Some of these modifications are accompanied with a significant decrease of the chemical stability of the ligand scaffold towards degradation, and ligand fragmentation has been observed in several cases.[4]

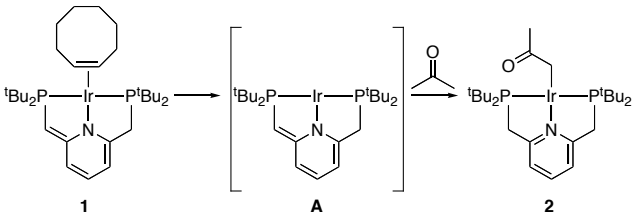
In part due to their high modularity, various pincer metal complexes have been developed that enable challenging bond making and breaking.[5] In some cases, the rigidly chelating bonding mode has been exploited to stabilize crucial intermediates, and to provide mechanistic insights. In other cases, the variability has been crucial for imparting high catalytic activity. While significant progress in cross-coupling catalysis has been achieved and reviewed,[6] perhaps the most remarkable results have been accomplished in the activation and cleavage of typically unreactive bonds, such as C–H, N–H, and O–H bonds, and also C–C and C–heteroatom bonds. This *Perspective* aims to overview the most significant advances, both in terms of mechanistic understanding and catalytic performance of pincer metal complexes in cleaving such unreactive bonds. An excellent review has appeared recently on PCP iridium-catalyzed dehydrogenation of alkanes and amine boranes,[7] and these reactions are thus not discussed in any depth here. Similarly, the iridium-mediated formation of carbenes from the activation of methyl ethers and amines via double α-H elimination, and ensuing catalytic applications have been summarized in a recent account.[8,9]

Activation of C–H bonds

Dehydrogenation of unactivated alkanes has been most efficiently performed with PCP iridium complexes as catalysts and turnover numbers up to 3000 have been achieved with optimized pincer scaffolds.[7] The working mode of the catalyst has been thoroughly investigated by kinetic and theoretical studies, and concurrent isomerization reactions as well as product inhibition effects have been identified. An analogous PCP rhodium complex comprising an agostically bound methane molecule, long postulated as a crucial intermediate of the catalytic cycle, has recently been isolated and structurally characterized.[10]

Cleavage of activated C(sp^3)–H bonds

The PNP iridium(III) complex **1** activates a C–H bond of acetone stoichiometrically (Scheme 1).[11] In this complex, the ligand is not aromatic and comprises an exocyclic double bond. Aromatization is induced upon protonation of the benzylic position, which also transforms the anionic amide donor into a neutral pyridine system. This aromatization is reversible and deprotonation of **2** has been demonstrated to occur at the benzylic position, thus reverting the formally monoanionic PNP pincer chelate. Cooperative participation of the ligand in the C–H bond activation of acetone has been postulated, involving the addition of the C–H bond across the metal-ligand unit. Deuterium labeling studies support a stepwise process including initial oxidative C–H activation at iridium and subsequent transfer of the hydrogen to the benzylic position of the ligand with concomitant aromatization. Theoretical analyses (DFT) support the proposed mechanism and predict the tricoordinate PNP iridium complex **A** as a critical intermediate.

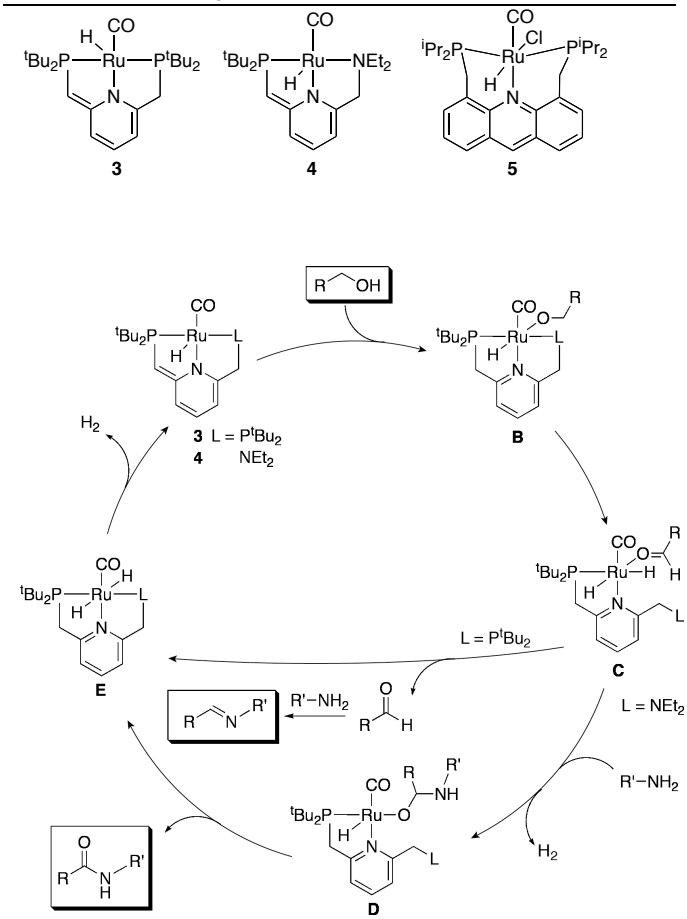


Scheme 1. PNP iridium-mediated activation of acetone.

The propensity of these PNP-type pincer ligands in cooperating in bond activation processes has been further exploited in the Ru-catalyzed dehydrogenative coupling of alcohols (Table 1).[12] In the presence of primary amines, either imines or amides are formed, depending on the donor sites at the pincer ligand. With the PNP ruthenium(II) complex **3**, imines are produced,[13] while the PNN analogue **4** affords amides.[14] In either system, the dehydrogenation activity of the ruthenium pincer complex is critical for high catalyst activity. Both imine and amide formation have been proposed to be sequential processes involving first dehydrogenation of the primary alcohol to the aldehyde, and subsequent reaction with the amine. Generally, a Schiff base-type reaction ensues, thus producing imines. The selectivity of complex **4** to generate amides thus implies that the carbonyl group remains coordinated when attacked by the amine, hence forming the hemiaminal within the ruthenium coordination sphere. Alternatively the hemiaminal intermediate of the Schiff base reaction may bind to the ruthenium center after being formed. In either case, an intermediate **B** is proposed, which can undergo a second dehydrogenation involving C–H bond cleavage to afford the amide product (Scheme 2). The mismatch in the PNN ruthenium complex between the soft metal center and the hard amine unit increases the hemilability of the pincer ligand and thus favors carbonyl coordination and hence amide formation. In contrast, the two soft phosphine donors in the PNP ligand bind stronger to ruthenium and P–Ru dissociation is disfavored. Hence, this complex releases the carbonyl intermediate rapidly and the reaction with the amine occurs as under normal Schiff base conditions to generate imines selectively. In agreement with this mechanistic proposal, secondary alcohols are less reactive and secondary amines are not incorporated at all.

Table 1. PNP iridium-catalyzed dehydrogenative coupling of alcohols

alcohol	reagent	catalyst	product	ref
R⌒OH	R'⌒NH$_2$	**3**	R⌒N⌒R'	13
R⌒OH	R'⌒NH$_2$	**4**	R(O)N(H)R'	14
R⌒OH	R⌒OH	**4**, **5**	R(O)OR	14, 15
R⌒OH	R⌒OH	**5**	R(O)(OR)OR	15
R"–OH	R(O)OR'	**4**	R(O)OR"	16



Scheme 2. Proposed catalytic cycle for the dehydrogenative coupling of alcohols and amines to form imines or amides.

In the absence of reactive amines, homocoupling of alcohols becomes the predominant pathway with complex **4** or **5**.[14,15] With less bulky substituents at the pincer donor groups, esters are formed, while sterically congested metal centers as in **5** lead to the predominant formation of acetals. Efficient ester formation from alcohols requires the addition of a base.[15] Along similar concepts, catalytic transesterifications have been successfully accomplished upon reacting esters and

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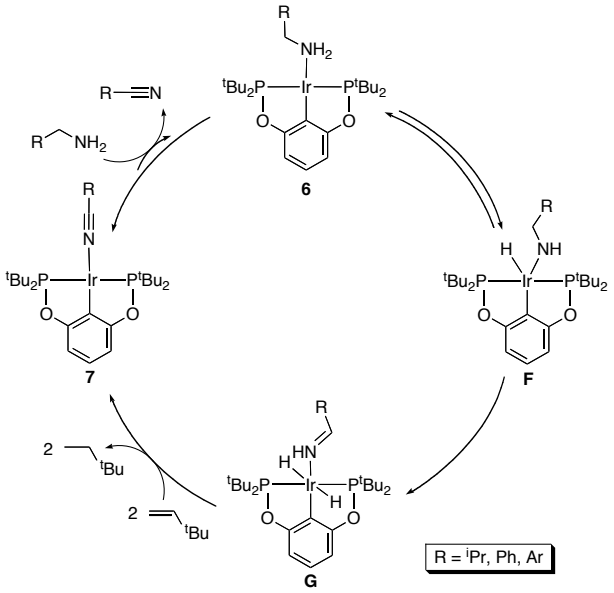
primary alcohols in the presence of complex **4**.[16]

The PCP iridium complex **6** is an efficient catalyst for the oxidation of primary amines to nitriles (Scheme 3).[17] Efficient double dehydrogenation has been achieved in the presence of *tert*-butylethylene as sacrificial hydrogen acceptor. Detailed mechanistic work involving a combination of competition experiments, isotope labeling studies, and kinetic analyses have identified three potential resting states of the catalyst, **6**, **7**, and **F**, which are interconnected via two pre-equilibria. Not surprisingly, a hard step is the substitution of the nitrile product from the coordination sphere of complex **7** by a new amine substrate (K ~ 550). Subsequent reversible N–H oxidative addition is followed by β-hydrogen elimination to produce **G** as the rate-limiting step, indicated by the substantial kinetic isotope effect of 2.8(2).

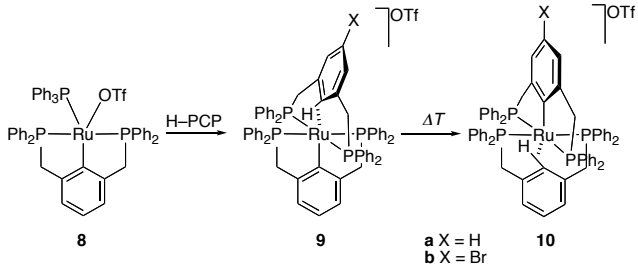


Scheme 3. PCP iridium-catalyzed dehydrogenation of primary amines.

Cleavage of C(sp^2)–H bonds

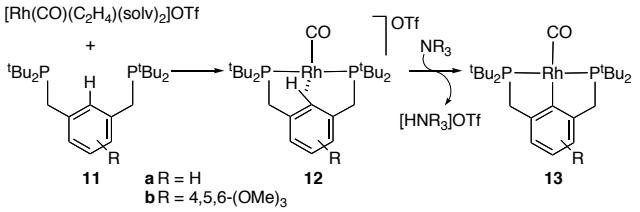
Cyclometalation is typically supported by initial heteroatom coordination followed by C–H bond activation.[18] Since pincer ligands contain two such potential anchoring sites for metal coordination, metal-mediated activation of the C_{aryl}–H bond in the ligand precursor is very common in pincer chemistry and represents one of the oldest and most frequently used strategies to introduce the metal center.[19] Here, only special cases are highlighted, such as C–H bond activations that are not heteroatom-assisted or that are incomplete and allow relevant intermediates to be stabilized and investigated.

Upon coordination of a second PCP ligand to the PCP ruthenium complex **8**, the agostic intermediate **9** has been isolated. This complex features one cyclometalated PCP ligand and one *P,P*-bidentate coordinating H–PCP ligand (Scheme 4).[20] Crystallographic analysis strongly suggests an agostic interaction between the ruthenium center and the C–H bond of the non-cyclometalated ligand. In solution, NMR spectroscopy has indicated a resonance of this proton at 1.2 ppm, thus being magnetically neither a hydride nor an aryl-bound hydrogen. Extensive ^{31}P NMR spectroscopic investigations and isotope labeling experiments have revealed a dynamic behavior of this hydrogen nucleus, involving migration from the non-cyclometalated ligand to the cyclometalated one. Further evidence for such proton migration has been obtained upon introducing a substituent on one of the arene fragments (**9b**, X = Br), which allows the two PCP ligands and hence complexes **9** and **10** to be differentiated. Base-mediated abstraction of the fluxional proton has been unsuccessful.



Scheme 4. Agostic interaction in a PCP ruthenium complex.

A structurally related agostic complex that may be regarded as a stabilized intermediate of a cyclometalation reaction has been isolated from $[Rh(CO)(C_2H_4)(solv)_2]OTf$ and different PCP ligand precursors (Scheme 5).[21] Complex **12** features an agostic interaction involving η^2-coordination of the C–H bond to the rhodium(I) center. This bonding mode, confirmed by X-ray crystallography, is preserved in solution as indicated by the unusual chemical shift of the *ipso* proton (δ_H 4.1 ppm) and its magnetic coupling to the rhodium center. The substantial upfield shift suggests that the proton has lost its aromatic character. Analogous products form when the central arene unit is functionalized with methoxy substituents. Apparently, the major metal-ligand interaction is due to the agostic interaction rather than due to an arenium-type limiting resonance form. In an agostic structure, the positive charge is formally located on the metal center, and not on the ligand as in arenium-type species. A rationale for this observation may rely on the fact that rhodium(I) is electron-rich and relatively soft, favoring π–backbonding rather than σ–donor interactions with ligands. In related complexes containing more electrophilic palladium(II) and platinum(II) centers, the arenium structure seems to contribute stronger (see below). In contrast to complex **9**, the proton in **12** is acidic and has been successfully abstracted with a weak base in order to complete the cyclometalation process, thus yielding the PCP rhodium complex **13**. It is worth noting that slight modifications in the metal precursor markedly decrease the stability of complex **12**. With $[RhCl(CO)_2]_2$, for example, the PCP ligand precursor **11** undergoes rapid cyclometalation to give **13** as the exclusive product.



Scheme 5. Agostic interaction and acid-lability of the agostic hydrogen in a PCP rhodium complex.

Apart from these mechanistic insights involving intramolecular C–H bond activation of the pincer ligand itself, numerous studies report on intermolecular activation of C(sp^2)–H bonds.[11,22] A PNP ruthenium polyhydride complex has been shown to cleave aromatic C–H bonds reversibly. This reactivity pattern has been employed for catalytic H/D exchange using C_6D_6 as deuterium source.[23]

Ligand cooperativity as evidenced in PNP and PNN pincer complexes is an attractive concept, and it is tempting to consider similar reaction patterns in the PNP iridium system used by Grubbs and coworkers for the formation of carbene complexes from methyl ethers and amines. In PCP iridium-catalyzed alkane dehydrogenation, however, all mechanistic evidence obtained thus far suggests a different reaction pathway that does not invoke de- and re-aromatization of the aryl ligand.[7] In addition, a number of ligand scaffolds that lack the possibility to reversibly de-aromatize are known to activate C–H bonds. For example, the PNP iridium complex **14** comprising oxo-linkers between the pincer arms and the central pyridine unit would generate a highly reactive oxonium species upon dearomatization (Fig 2). Isotope exchange within the metal-bound aryl or methyl group of **14** is promoted by protic reagents such as CD_3OD or D_2O and includes the formation of a protonated complex **15**, which has been fully analyzed.[24] Transient formation of a π-bound benzene ligand (from **15a**) or an agostically bound methane complex (from **15b**) and subsequent site exchange would account for the observed H/D substitution process. Stoichiometric C–H activation of benzene with PNP rhodium complexes that contain silicon substituents at the central amide,[25] and with iridium complexes comprising a monoanionic PSiP pincer ligand presumably occurs without ligand participation either.[26]

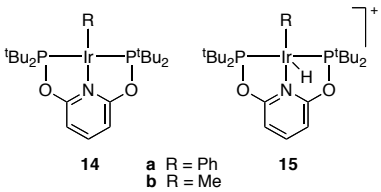


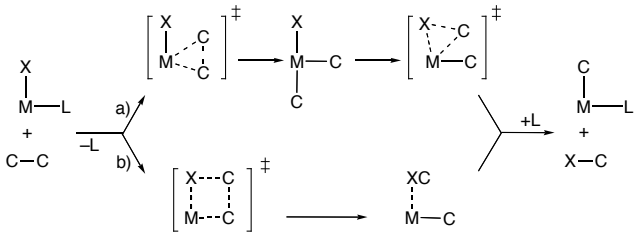
Fig. 2. Neutral PNP iridium complex **14** and cationic complex **15** which interchanges hydrogens between the metal-bound site and R.

Activation of C–C bonds

While C–C bond formation is a mature field, most notably due to the significant advances in metal-mediated cross-coupling reactions,[27] the reverse process, *i.e.* C–C bond cleavage, is still at its infancy. Pincer complex formation has been used as a driving force to entail alkyl-aryl C(sp^3)–C(sp^2) bond cleavage.[1,5,28] Mechanistic investigations on the C–C bond activation process and also on its microscopic reverse, *viz.* C–C bond formation, provided insights into the intimate steps of the bond cleavage process and several crucial intermediates have been stabilized due to the unique steric and electronic impact of the pincer-type ligands.

Mechanistic investigations

Phosphine-containing PCP, PCN, and PCO pincer ligands have been used in combination with rhodium and iridium to study mechanistic aspects of C–C bond cleavage, while NCN platinum systems allowed for the stabilization of intermediates during C–C bond formation. In rhodium(I) and iridium(I) chemistry, an oxidative addition pathway for C–C bond activation has been discussed extensively, while a substitution process has been put forward for platinum(II) complexes (Scheme 6). Theoretical considerations support this general picture,[29] yet it should be noted that despite the difference in terminology, the overall reaction coordinate of both substitution and oxidative addition are highly similar. Distinction often requires evoking minor differences in metal-ligand and ligand-ligand interactions.



Scheme 6. Generic representation of C–C bond activation by a) oxidative addition (insertion) followed by optional reductive elimination (nucleophilic M); b) by substitution, including bond metathesis and electrophilic pathways.

Upon combining these seemingly different concepts, a detailed and comprehensive model of the pincer-metal mediated C–C bond activation process emerges (Scheme 7). Many intermediates of this process have been characterized spectroscopically, and often also crystallographically. Two conclusions are probably most relevant: firstly, the intrinsic step of C–C bond making and breaking appears to be highly similar in oxidative addition and substitution-type reactions. Secondly, mechanistic investigations on C–C bond formation and on C–C bond cleavage provide a converging picture, which suggests a common reaction coordinate.

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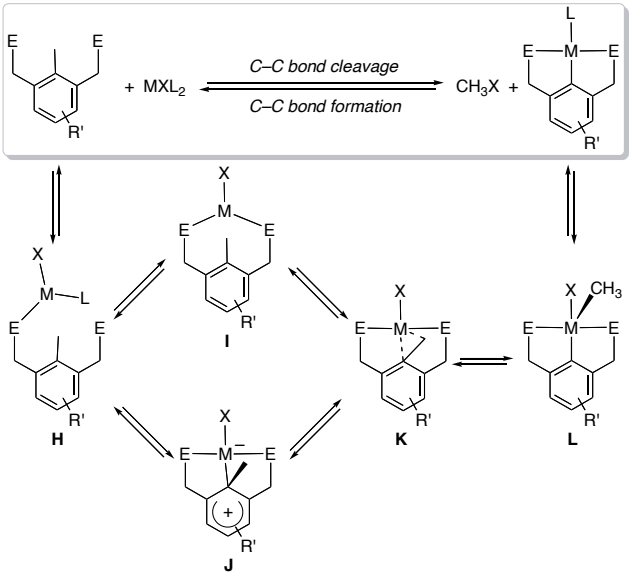
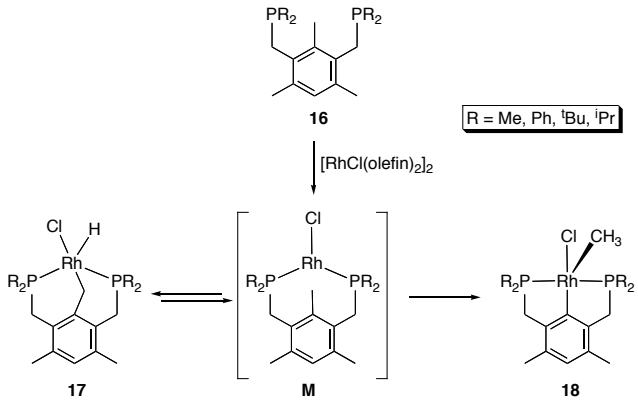


Scheme 7. Postulated mechanism of C–C bond making and breaking within a pincer scaffold.

The stability of the intermediates is highly dependent on the nature of the metal center and the donors E, and an intermediate in one M/E set may become a transition state in a different metal/ligand combination. For example, in NCN platinum chemistry (E = NMe_2), intermediates **J** and **L** have been characterized, while structure **K** is supposed to be the transition state in between. Complexes of type **K** are more stable in PCP rhodium complexes and have been isolated as an intermediate of C–C bond activation. Likewise, the coordination compound **I** has been postulated as a short-lived intermediate in PCP rhodium complexes. Upon changing the donor array to a PCN pincer ligand, this species is sufficiently stable to be characterized.[30]

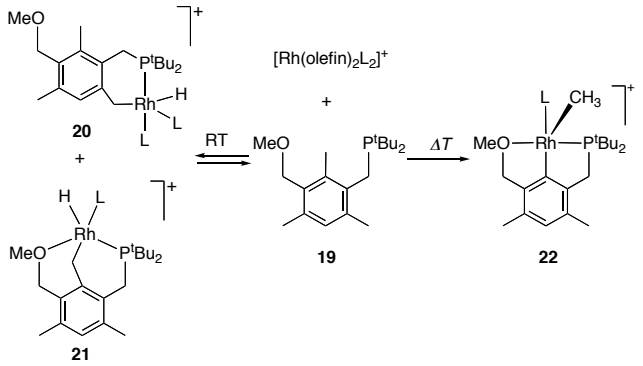
Metalation of the PCP ligand precursor **16** with a rhodium(I) salt results in C_{aryl}–C_{alkyl} and C_{alkyl}–H bond activation (Scheme 8).[28*b*] Both processes are thermodynamically and kinetically very similar and subtle changes in the ligand parameters hence strongly affect the reaction outcome. For example, PPh_2 donors induce C–H bond cleavage to afford **17**. Only at elevated temperatures and under H_2 atmosphere, C–C bond activation is observed. In contrast bulky P^tBu_2 donors promote C–C bond activation already at room temperature and the aryl complex **18** is the exclusive metalated product. Similarly, replacing one phosphine donor by a harder NEt_2 group or employing less basic phosphinite donors results in fast and exclusive C–C bond cleavage at room temperature and below. These outcomes indicate that steric rather than electronic effects play a dominant role for the thermodynamic preference of C–C over C–H activation. Steric congestion has been suggested to force the metal orbitals into a rigid orientation that is directed towards the C–C bond. Moreover, the C–H bond activation is reversible while the C–C activation is not, unless chemically induced, *e.g.* by phosphine-induced metal dissociation.[31] The higher bond dissociation energies required for C–C bond activation as compared to C–H bond breaking is evidently compensated by the higher M–aryl bond strength and the formation of two five-membered rather than six-membered metalacycles.



Scheme 8. Reversible C–H and irreversible C–C bond activation in rhodium complexation of PCP ligand precursors.

Kinetic investigations of these reactions have identified the coordination compound **M**, *i.e.* an analogue of **I** (*cf* Scheme 7), as a common intermediate of both, C–H and C–C bond cleavage. Remarkably, formation of this intermediate, and not C–H or C–C bond activation is rate-determining. While displacement of a weakly bound olefin ligand in the rhodium precursor $[RhCl(olefin)_2]_2$ may be fast, formation of the 8-membered metalacycle in **M** is obviously less favored, especially due to the possible formation of di- and polymeric coordination compounds. With appropriate donor groups, the postulated coordination complex akin to **M** has been characeterized in solution at low temperature.[30] When using kinetically less reactive platinum(II), the bidentate diphosphine coordination is even further stabilized.[32]

The transoid bidentate chelation of the donor groups in **M** is pivotal for entailing C–C bond activation. When using monophosphine ligand precursors that lack a second donor group, C–H bond activation occurs selectively and no C–C bond cleavage has been observed.[33] With the related PCO pincer ligand precursor **19**, C–H activation is kinetically preferred at room temperature (Scheme 9).[34] However, this reaction is not selective and produces a mixture of **20** and **21**, indicating that both C–H bonds in *ortho* position to the phosphine are activated. Upon heating, C–C bond activation takes place exclusively at the position *ortho* to both the O and P donor groups to afford **22**. These reactivity patterns illustrate the reversibility of C–H bond activation process, and more importantly, that bidentate ligand bonding is essential for C–C but not for C–H bond activation. Furthermore, these conclusions provide a rationale for the inherent difficulties encountered when probing catalytic or intermolecular C–C bond activation. Undoubtedly, though, the potential to accomplish and (thermally) trigger the activation of such otherwise unreactive bonds illustrates the extraordinary potential of pincer-type chelation for tuning unique metal-mediated processes.

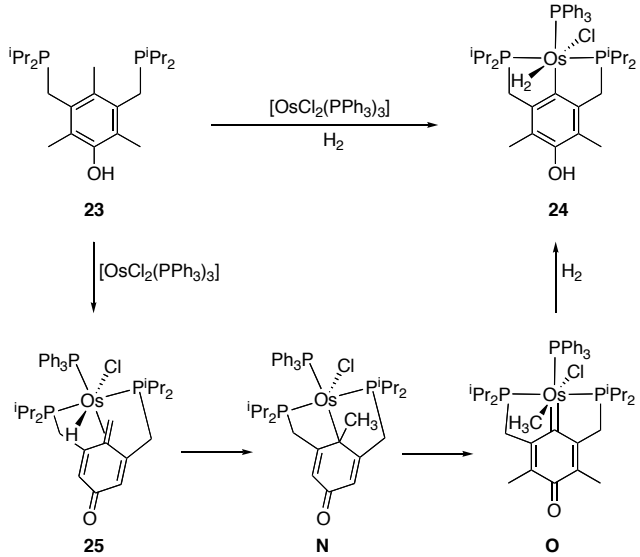


Scheme 9. Reversible C–H and regioselective C–C bond activation in PCO rhodium complexes.

The activity of the rhodium center in intermediate **M** towards C–C bond cleavage is strongly associated with its tricoordinate 14e configuration. Consequently, the bond activation process reveals a strong solvent dependence.[35] In coordinating MeCN, stabilization of the rhodium center and the formation of square-planar complexes depletes the concentration of the 14e intermediate, and C–H bond activation becomes the predominant reaction pathway. Conversely, less coordinating solvents such as tetrahydrofuran favor C–C bond cleavage.

Similarly, substitution of the metal center from rhodium to iridium, ruthenium, or platinum has direct consequences.[31] While activation of the C–C bond in the PCP ligand precursor **16** occurs smoothly at room temperature with rhodium(I), only C–H bond activation is observed with the iridium(I) homologue.[31*b*] Substantial heating is required to direct the course of the reaction towards C–C bond activation. These results underline the increasing stability of Ir–hydride species compared to their Rh analogues, and presumably also the higher nucleophilicity ascribed to the rhodium(I) center.[30]

The strong influence of the metal on the C–C *vs* C–H bond activation selectivity is further illustrated in osmium(II)-mediated C–C bond cleavage.[36] Exposure of $[OsCl_2(PPh_3)_3]$ to the hydroxy-functionalized PCP ligand precursor **23** containing basic P^iPr_2 donors induces C_{aryl}–C_{alkyl} bond cleavage and yields complex **24**, when the reaction is performed in the presence of H_2 (Scheme 10). In the absence of H_2, the quinone methide **25** is formed selectively as a result of C–H bond activation. A dynamic process has been suggested that involves interconversion of the quinone methide **25** to its arenium tautomer **N**, resulting from insertion of the exocyclic olefin into the Os–H bond. An analogous product has been trapped upon addition of CO. A subsequent shift of the methyl group to osmium followed by hydrogenation of intermediate **O** has been postulated to account for the formation of complex **24**, thus suggesting the quinone methide **25** to be an early intermediate in the direct formation of **24** from **23.**



Scheme 10. Osmium-mediated C–H and C–C bond cleavage.

Arenium complexes have been extensively studied earlier in NCN platinum chemistry.[28*a*] They are readily prepared from the solvento complex **26** and are resistant towards air and moisture. The crystal structures of several complexes show consistently that the platinum center is bound to the aryl carbon only.[37] In all structures, the Pt···C_{alkyl} distance is far too large for postulating any agostic resonance structure contribution (*cf* **K** in Scheme 7). In addition, these platinum-stabilized arenium complexes readily react with nucleophiles at their *ortho* and *para* position and afford platinum-substituted cyclohexadienyl derivates. This dearomatization process indicates that the positive charge is localized on the aromatic ring rather than on the metal center. Arenium structures have been proposed to result from a 1,2-sigmatropic shift of the alkyl group from the metal center in the (alkyl)(aryl) complex **27** to the aryl carbon in **28** (Scheme 11), thus relating structures **J** and **L** directly (*cf* Scheme 7). Spectroscopic identification of this migration has been achieved by incorporating electron-donating substituents on the aryl ring (R = OH, OMe),[38] a well-known concept in electrophilic aromatic substitution. Such a modification increases the reactivity of the *ipso* carbon and of the platinum center in **26** and allows (alkyl)(aryl) complexes to be stabilized with a variety of different alkyl substituents other than MeI. In the case of the (benzyl)(aryl) complex **27**, a color change has been observed upon formation of **28**.[38*a*] Analysis of this transformation by UV-vis spectroscopy has revealed an isosbestic point, thus indicating the presence of an equilibrium between the two species **27** and **28** exclusively. This equilibrium implies that alkyl migration between **27** and **28**, *viz.* the microscopic C–C bond making and breaking step, is fully reversible. Consequently the actual C–C bond formation is the exact microscopic reverse of the C–C bond cleavage process in these platinum pincer complexes.

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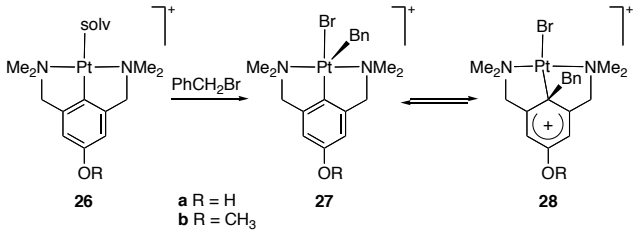


Scheme 11. Reversible arenium formation in NCN platinum complexes.

The alkyl group migration has been postulated to include a 3-centered non-polar transition state reminiscent to **I** (*cf* Scheme 7).[39] Similar transition states have been proposed in the C–C bond activation using PCP rhodium complexes.[40] Molecular orbital considerations suggest two distinct interactions that contribute predominantly to the stability of **K**. One interaction (Fig 3a) is characterized by overlap of an sp^3 orbital of the formally cationic alkyl group with the filled d_σ orbital of the d^8 metal center, having predominant d_{z^2} character, and simultaneous interaction with the distorted p_π orbital of the aryl carbon. Shuttling of the alkyl cation from the metal closer to the carbon obviously increases C–C bond overlap and thus induces a rehybridization of the p_π orbital to an sp^3 orbital, and dearomatization ensues upon C–C bond formation, leading to arenium structures. The microscopic reverse C–C bond cleavage process thus includes the metal-induced depletion of electron density in the C–C bond, a process that is favored with electrophilic metal centers such as platinum(II).[29]

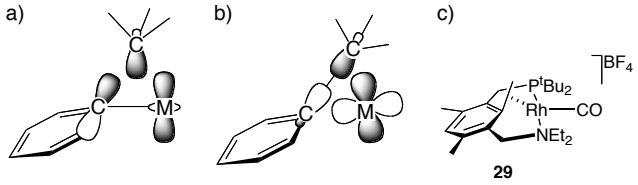


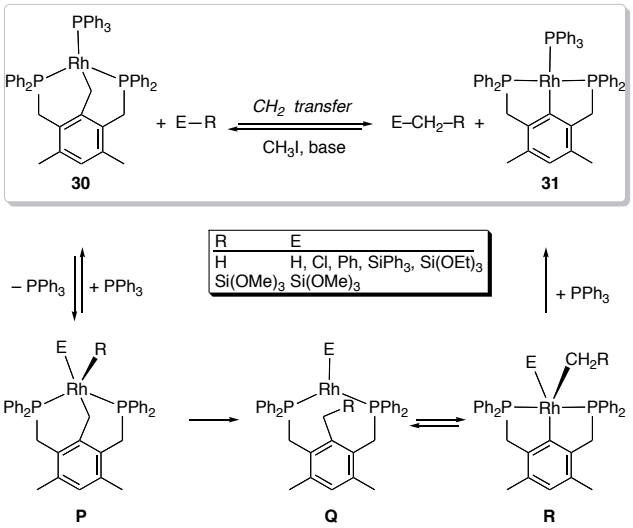
Fig. 3. a) Orbital interactions relevant for C–C bond activation via sigmatropic 1,2-shift of a cationic alkyl fragment along the C–M bond (electrophilic activation, electron removal from the C–C σ orbital); b) agostic interaction en route to oxidative addition (population of the C–C σ^* orbital via backbonding); c) complex **27** as a structural model comprising agostic interactions.

A second contribution consists of a metal d_π electron donation into the C–C σ^* orbital bond and leads to an agostic interaction that eventually climaxes in an oxidative addition (Fig 3b). Stronger donor ability of the ligands E and electron-rich, nucleophilic metal centers such as rhodium(I) or iridium(I) will thus increase the electron density in the C–C antibonding orbital (π backbonding) and C–C bond cleavage along this reaction coordinate will be facilitated. These considerations may explain the different stability of the intermediate complexes in NCN platinum(II)-mediated C–C bond making and breaking as opposed to analogous processes at PCP iridium(I) and rhodium(I) centers. The former stabilizes arenium species due to strong C–M σ interactions with the electrophilic platinum(II), while the latter prefer an agostic bonding mode that allows the nucleophilic metal centers to be bound to a π–accepting ligand.

In agreement with this model, stabilization of an agostic complex has been achieved by appropriate modification of the donor group (**29**, Fig 3c).[40] Upon substitution of one phosphine donor by a NEt_2 group, the electron density at the cationic rhodium center is reduced to such an extent that the agostic complex is moderately stable and thus does not represent a transition state anymore. The electronic balance which determines whether C–C bond activation is completed or arrested at the agostic stage is very subtle. Using $[Rh(C_2H_4)_2(solv)_n]^+$ rather than $[Rh(CO)(C_2H_4)(solv)_2]^+$ as metal precursor leads to clean C–C bond cleavage.

Methylene Transfer

Interesting synthetic opportunities emerge from reactions that are under kinetic control, leading to products from C–H rather than C–C bond activation. For example, complexation of rhodium(I) with the CH_3–PCP ligand precursor **16** bearing PPh_2 donors induces C–H bond activation and affords the benzyl complex **30** (Scheme 12). The corresponding platinum(II) complex with a coordinated [PtCl] unit—isolobal to the $[Rh(PPh_3)]$ fragment—has been prepared even with bulky P^tBu_2 groups in the pincer scaffold. In these complexes, C–C bond activation has been induced by addition of H_2 or HCl. Apparently, H_2 and HCl favor reductive C–H elimination, *i.e.* the backward reaction from C–H bond activation and formation of the intermediate **Q** (Scheme 12, see also **I** in Scheme 7). Simultaneously, the activation energy for C–C bond activation is reduced, rendering C–C bond activation more favorable than C–H bond activation. The overall process from **30** to **31** may formally be considered as a CH_2 transfer to an appropriate acceptor such as H_2 or HCl, leading to the production of CH_4 and CH_3Cl, respectively.[41] Similarly, benzene, hydrosilanes, and disilanes have been successfully employed as acceptors, providing toluene, R_3SiCH_3, and $R_3Si–CH_2–SiR_3$, respectively.[31d,41]



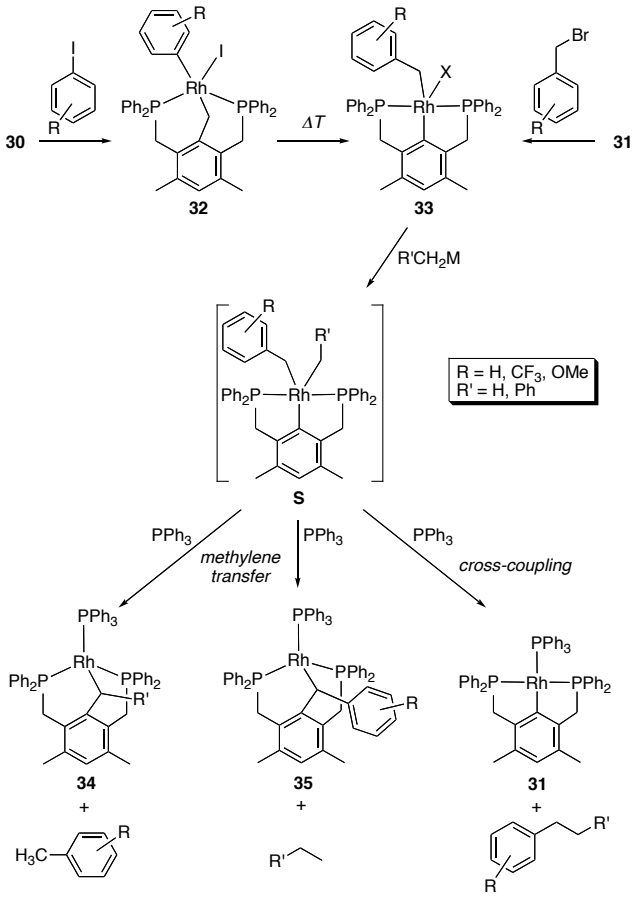
Scheme 12. Methylene transfer from a PCP rhodium complex to an acceptor molecule E–R.

Mechanistic and theoretical investigations indicate that the process involves a sequence that is initiated by oxidative

addition of the acceptor E–R to the benzyl complex (**P**, Scheme 12).[42] Rate-limiting C–R reductive elimination and subsequent C–C bond activation is followed by irreversible reductive E–CH_2R elimination from **R**, thus completing the CH_2 transfer and affording the PCP rhodium complex **31**. Notably, Rh–phosphinite complexes reminiscent of **R** have been shown to undergo apparent α–hydrogen elimination, thus providing an alternative mechanism for the release of the CH_2 fragment (for R = H).[43]

The absence of any products originating from double CH_2 insertion indicates that C_{aryl}–C_{alkyl} bond activation is an intramolecular process. The methylene transfer reaction can be reversed by addition of CH_3I as a CH_2 source to complex **31**, and subsequent base-promoted abstraction of HI.[41] This procedure regenerates the benzyl complex **30**. Similarly, $SnMe_4$ in the presence of KO^{t}Bu has been shown to induce methylene insertion into the Rh–C_{aryl} bond.[44] Catalytic CH_2 transfer is thus possible and has indeed been demonstrated.[45] While the overall process is remarkable, the observed rates (10 turnovers in 48 h) require further optimization in order to become synthetically useful.

Methylene transfer to benzene requires high temperatures and long reaction times, which is in agreement with oxidative addition of the acceptor molecule as the rate-limiting step of this reaction. Consistently, the use of an aryl halide promotes fast oxidative addition to **30** already at room temperature (Scheme 13).[42] The formed complex **32** undergoes a methylene transfer at slightly elevated temperatures to yield the (benzyl)(aryl) complex **33**. This complex is also accessible from the PCP rhodium complex **31** via oxidative addition of substituted benzyl bromide. Reductive elimination from **33** is initiated only upon addition of a coordinating ligand such as PPh_3 and a carbanion R'CH_2^- as nucleophile, presumably via transmetalation and formation of the postulated triorgano-rhodium complex **S**. Several competing reactions then ensue: cross-coupling of the two monodentate ligands gives complex **31** as the organometallic product. Alternatively, one of the monodentate carbanions may reductively migrate to the pincer ligand *ipso* carbon to produce an intermediate similar to **I** (*cf* Scheme 7), corresponding to a back transfer of the methylene group. Upon C–H bond activation, complexes **34** and **35** are obtained via migration of the nucleophile and the benzyl group, respectively. Variation of the substitutent R at the benzylic group has evidenced a strong electronic control. Electron-releasing groups (R = OMe) increase the migration tendency and yield predominantly **35**, whereas acceptors (R = CF_3) migrate slower and hence produce **34** and significant amounts of cross-coupling products.



Scheme 13. Methylene transfer and cross-coupling mediated at a PCP rhodium center.

Activation of C–E bonds

The catalytic activity of pincer complexes in cross-coupling reactions implies a high potential of these complexes to activate C–B and C–Si bonds used for Suzuki-Miyaura and Hiyama-type reactions, respectively, and of course also a wealth of C–X (X = Cl, Br, I, OTf) and C–M bonds (M = Mg, Al, Sn, Zn, etc).[6] Here, only strong C–E bond activation will be discussed, including cleavage and redox reactivity of C–N, C–O, and C–F bonds.

C–N bond activation

Metal-mediated C–N bond activation is little explored in pincer chemistry. Activation of a C_{benyzl}–N bond in a pincer-type ligand precursor has been observed in the presence of $[RhCl(coe)_2]_2$ and H_2.[46] While the reaction is catalytic (up to 21 TONs), the mechanism has been postulated to not involve pincer-type metal bonding.

A PNN ruthenium complex related to **1** (*cf* Table 1) catalytically cleaves amides to amines and alcohols under hydrogen pressure.[47] This reduction is complementary to $LiAlH_4$-mediated amide reduction. Most likely, an aromatization/dearomatization sequence of the heterocycle occurs, thus constituting the microscopic reverse of the amide synthesis discussed above (*cf* Scheme 2). The possibility to switch the reactivity from dehydrogenation (amide synthesis)

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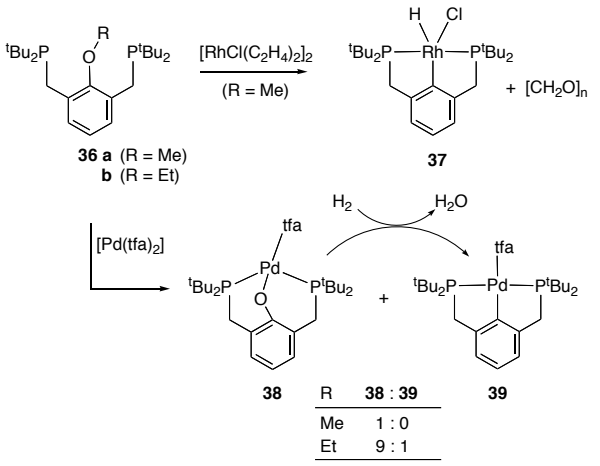
to hydrogenation (amide cleavage) by changing the reaction atmosphere illustrates the robustness of the pincer metal unit in these transformations.

C–O bond activation

The cleavage of C–O bonds has been demonstrated in stoichiometric and catalytic processes. Stoichiometric C_{aryl}–O bond scission occurs upon heating the pincer ligand precursor **36a** in the presence of $[RhCl(ethene)_2]_2$ (Scheme 14).[48] The PCP rhodium complex **37** is formed along with formaldehyde, and no activation of the less strong C_{alkyl}–O bond has been observed. Most conceivably, this high chemoselectivity is due to a mechanism that is related to C_{aryl}–C_{alkyl} bond cleavage (*cf* Schemes 10 and 11), involving a *P,P*-bidentate coordination of **36a** and subsequent formation of an (aryl)(methoxy) rhodium(III) intermediate that may undergo facile *β*–hydrogen elimination and extrusion of formaldehyde. Mutually transoid bidentate coordination of the phosphines appears to be an essential factor for directing the metal center to the C_{aryl}–O rather than the C_{alkyl}–O bond. With related monophosphine ligand precursors, cleavage of the weaker C_{alkyl}–O bond has been observed.[49] Furthermore, bulky ^{t}Bu-substituents at the phosphorus give better results than phenyl groups.

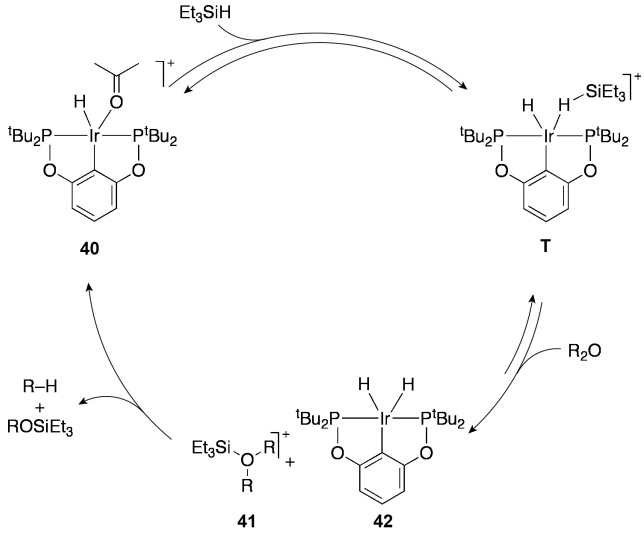


Scheme 14. Rhodium- and palladium-mediated C–O cleavage within a pincer scaffold.

With harder and more electrophilic palladium(II) and nickel(II) centers, Lewis acid-base complexation to oxygen becomes more relevant, and consequently, C_{alkyl}–O bond activation as in monophosphine ligands is observed (**38**, Scheme 14).[48,50] The bond cleavage selectivity is dependent on the substitution pattern at oxygen. Larger substituents decrease oxygen-metal interactions and accordingly, C–O activation in the ethoxy PCP ligand precursor **36b** is less selective than in the methoxy analogue and results in both C_{alkyl}–O and C_{aryl}–O bond cleavage (9:1 ratio at 130 °C).

The ring strain imposed by the two six-membered metalacycles in complex **38** has been exploited to develop an oxygen transfer process reminiscent of the methylene transfer reaction in related complexes. Oxygen extrusion from **38** in the presence of H_2 is achieved at high temperatures (180 °C) and yields the PCP palladium complex **39** and H_2O. Similarly, the (aryl)(methoxy) rhodium(III) intermediate has been successfully employed for transferring an alkoxide. Upon performing the rhodation of the precursor **36a** in the presence of $HSiR_3$, $MeOSiR_3$ has been obtained rather than formaldehyde along with complex **37**.

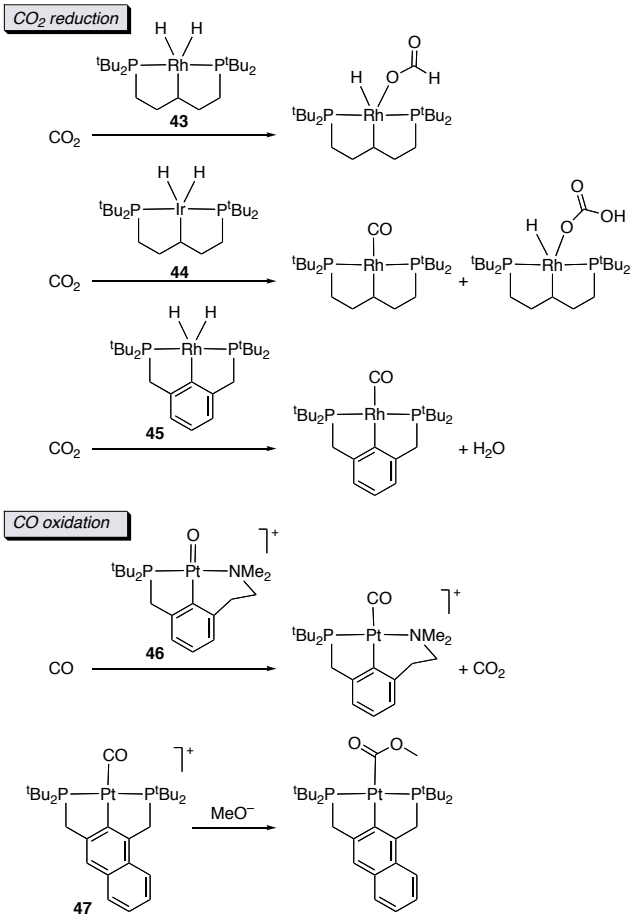
Catalytic C–O bond cleavage has been achieved with the cationic PCP iridium complex **40** in the presence of $HSiEt_3$ (Scheme 15).[51] A variety of primary, secondary, and tertiary ethers have been successfully cleaved at room temperature. Ethers with bulky alkyl groups undergo a single C–O cleavage and give one equivalent of alkane RH and the corresponding silyl ether $ROSiEt_3$. More basic and less bulky ethers engage in two sequential C–O bond cleavage reactions and produce two equivalents of alkane RH along with $Et_3SiOSiEt_3$. Mechanistic work suggests a process that involves reversible coordination of the silane to the iridium cation followed by hydride transfer from silicon to the iridium center, thus forming a silyl cation that is ether-stabilized. Subsequent C–O cleavage is promoted by the iridium dihydride intermediate, thus yielding the silyl ether and the alkane, and also regenerating the cationic complex **40**. This step is rate-limiting. The oxonium species **41** as the catalyst resting state along with the known dihydride **42** has been isolated and characterized crystallographically. With less basic ethers than Et_2O, the resting state shifts forward from the oxonium salt to the silane complex **T**, which is also relevant to the iridium-catalyzed dehalogenation of alkyl halides.[52]



Scheme 15. PCP iridium-catalyzed cleavage of ether bonds.

Conversion of CO and CO_2 has been probed with a variety of pincer metal complexes, motivated at least in parts by the environmental relevance of these small molecules. The rhodium dihydride complex **43** inserts dry CO_2 into the Rh–H bond and yields a PCP rhodium complex containing a formate ligand, corresponding to a formal reduction of CO_2 (Scheme 16).[53] The stability of the formate intermediate is strongly dependent on the nature of the metal center and on the type of pincer ligand. Changing the metal center in complex **43** to iridium affords the less stable formate complex **44** which disproportionates to a bicarbonate and a carbonyl iridium complex.[54] Similarly, modification of the anionic fragment

from an alkyl moiety to an aryl anion (complex **45**) transforms the formate complex into a transient, yet spectroscopically detectable intermediate that spontaneously eliminates H_2O to yield a rhodium(I) carbonyl complex.[55] Formally, this process involves the reduction of CO_2 to CO and thus constitutes the reverse of the water-gas shift reaction. The stoichiometric oxidation of CO to CO_2 has been achieved with the platinum(IV) oxo complex **46**.[56] Concomitant reduction of the metal center affords a cationic PCN platinum(II) complex containing a carbonyl ligand. A *C*-bound formate complex has been obtained upon reaction of the platinum complex **47** with NaOMe.[57] Hence formate fragments may be assembled either from CO_2 or from CO.

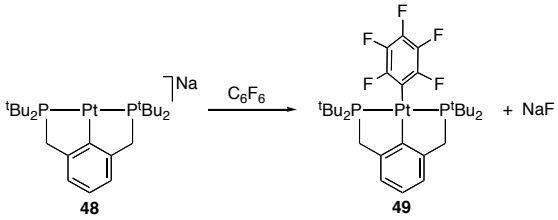


Scheme 16. Reactivity of pincer complexes towards CO_2 and CO.

C–F bond activation

The chemistry of the C–F bond is of high relevance, in particular for pharmaceutical applications. The bond is considered to be one of the strongest bonds and methods for C–F bond formation and scission are thus of paramount interest.[58] Cleavage of the C–F bond has been reported in a PNP titanium complex comprising a Schrock-type carbene ligand.[59] With fluoroarenes such as C_6HF_5, the C–H bond is activated selectively. Upon warming to 100 °C, C–F bond cleavage occurs via *β*-fluoride abstraction, resulting in a PNP–TiF complex and *ortho*-benzyne as side product, which has been identified by trapping experiments.

Stoichiometric C–F bond scission in hexafluorobenzene has been accomplished with the PCP platinum(0) complex **48** at –35 °C (Scheme 17), yielding the corresponding platinum(II) complex **49** containing a $C_6F_5^-$ ligand and NaF.[60] A radical mechanism has been postulated, involving a one-electron transfer from the platinum center to C_6F_6, thus generating a platinum(I) intermediate and a $[C_6F_6]^{\cdot-}$, which couple after loss of F^-.



Scheme 17. C–F bond cleavage by a PCP platinum(0) complex.

Activation of E–H bonds

N–H bond activation

A PCP iridium pincer complex comprising an aliphatic carbanionic moiety has been successfully employed for the activation of ammonia and hydrazine.[61] While only stoichiometric activation has been achieved, interesting transfer reactions may emerge from metal bound amides. Related work has demonstrated the stoichiometric activation of a N–H bond of various anilines mediated by complex **3** (*cf* Table 1). Ligand participation via heterocycle aromatization may be a key feature also in this activation process.[62]

O–H bond activation

Activation of the O–H bond in alcohols has been invoked in the activation of H_2 at the PNP iridium(I) complex **14b** (*cf* Fig 2).[63] The formation of the *trans* dihydride oxidative addition product implies an indirect activation process, presumably including first RO–H bond activation to form complex **15b** as a transient intermediate with RO^- as counterion. Subsequent heterolytic H_2 activation regenerates the alcohol, albeit with a proton stemming from H_2. Rapid incorporation of deuterium upon performing the reaction in the presence of D_2O or CD_3OD support the postulated reaction pathway.

Ligand assisted RO–H bond activation has been observed also in PNP platinum and palladium complexes, in which the PNP ligand is dearomatized.[64] In this case, the hydrogen is ultimately bound to the benzylic position, inducing aromatization of the heterocycle. The activity of this type of pincer complexes towards O–H bond activation has been further expanded to develop a process that allows for effective water splitting at complex **4** (Scheme 18).[65] The reaction includes cooperative fixation of water at the ruthenium center and the pincer ligand to give complex **50**, followed by thermally induced H_2 elimination, affording the dihydroxide **51**. Consecutive light-induced dissociation of H_2O_2 and disproportionation yields O_2 and H_2O. Intramolecular hydrogen transfer from the benzylic position of intermediate **U** to the ruthenium center and concomitant de-aromatization regenerates complex **4**. Isotope labeling experiments have demonstrated that the H_2O_2 formation is an intramolecular

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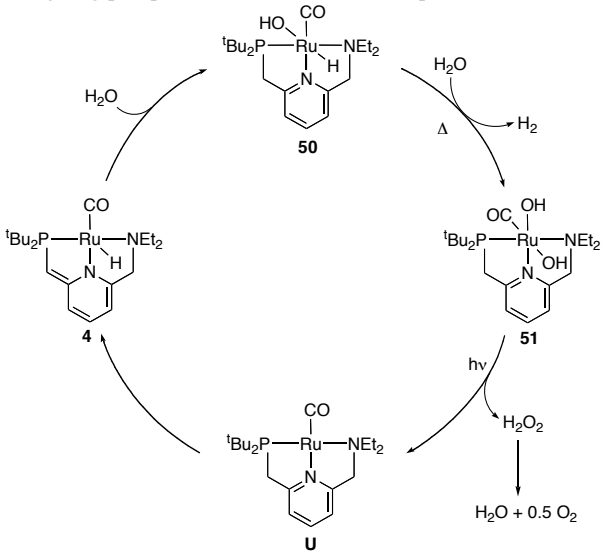
process rather than a consequence of a bimolecular reaction. Even though parts of the water splitting need to be sequentially pulsed by thermal and photochemical stimulation, the possibility to split water at a single metal center provides intriguing perspectives for further developments.



Scheme 18. Water splitting mediated by the PNP ruthenium complex **4**.

Si–H bond activation

Catalytic Si–H bond activation using the PCP iridium complexes **40** and **42** has been discussed together with C–O bond activation in ethers (*cf* Scheme 15). The same mechanism of silane activation has been exploited for the catalytic reduction of alkyl halides.[52] Elegant competition experiments have uncovered a pre-equilibrium involving iridium coordination either to RX or to $HSiEt_3$. This equilibrium is responsible for the unusual preference of catalyst **40** to convert pure RBr faster than pure RCl and much faster than RI. In mixtures, however, the expected reactivity sequence RI > RBr > RCl is restored, as the pre-equilibrium is shifted to $HSiEt_3$ coordination when the better coordinating iodoalkane is present only in minor quantities.

Both intra- and intermolecular Si–H activation has been observed at a platinum center bound to a PSiP pincer ligand.[66] Mechanistic studies may unravel intriguing differences between Si–H bond activation processes and the well-understood C–H bond activation.

Conclusions

Pincer ligands have provided an excellent platform for tailoring the activity of metal centers towards the cleavage of strong bonds that are typically unreactive. Both stoichiometric metal-mediated reactions as well as efficient pincer metal-catalyzed processes have been disclosed, many of which lacking precedence such as room temperature C–C bond making and breaking and the complete splitting of water at a single metal center. The high steric and electronic flexibility of the pincer ligand has been pivotal for uncovering mechanistic details that also provide guidelines for general transition metal-mediated reactions. Furthermore, pincer ligands show great potential to adapt to specific needs of the coordinated metal center, as illustrated for example by reversible ligand de- and re-aromatization, and by the accommodation of metals in various oxidation states (*cf* platinum(0) up to platinum(IV) within the same PCP pincer scaffold). Despite the remarkable progress achieved up to now, the enormous variability in pincer chemistry—*e.g.* through modification of the donor groups as well as in the central unit—may pave the way for further breakthroughs in bond activation processes, thus providing exciting perspectives for organometallic chemistry, organic synthesis, and materials science.

Notes and references

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1 (*a*) M. Albrecht and G. van Koten, *Angew. Chem. Int. Ed.*, 2001, **40**, 3750; (*b*) M. E. van der Boom and D. Milstein, *Chem. Rev.*, 2003, **103**, 1759; (*c*) D. Milstein, *Pure Appl. Chem.*, 2003, **75**, 445; (*b*) D. Morales-Morales and C. M. Jensen, eds., *The Chemistry of Pincer Compounds*, Elsevier, Amsterdam, 2007.
2 M. H. P. Rietveld, D. M. Grove and G. van Koten, *New J. Chem.*, 1997, **21**, 751.
3 For recent examples, see: O. V. Ozerov, L. A. Watson, M. Pink and K. G. Caulton, *J. Am. Chem. Soc.,* 2007, **129**, 6003; (*b*) A. Garcia-Camprubi, M. Martin and E. Sola, *Inorg. Chem.*, 2010, **49** 10649; (*c*) C. Gunanathan, B. Gnanaprakasam, M. A. Iron, L. J. W. Shimon and D. Milstein, *J. Am. Chem. Soc.,* 2010, **132**, 14763.
4 (*a*) S. J. Mitton, R. McDonald and L. Turculet, *Angew. Chem. Int. Ed.*, 2009, **48**, 8568; (*b*) H. Salem, L. J. W. Shimon, Y. Diskin-Posner, G. Leitus, Y. Ben-David and D. Milstein, *Organometallics*, 2009, **28**, 4791.
5 (*a*) S. Murai (ed.), *Top. Organomet. Chem.*, 1999, **3**; (*b*) K. I. Goldberg and A. S. Goldman, eds., in *ACS Symposium Series 885*, ACS, Washington, 2004.
6 (*a*) J. T. Singleton, *Tetrahedron*, 2003, **59**, 1837; (*b*) E. Peris and R. H. Crabtree, *Coord. Chem. Rev.*, 2004, **248**, 2239; (*c*) N. Selander and K. J. Szabo, *Dalton Trans.*, 2009, 6267; (*d*) N. Selander and J. K. Szabo, *Chem. Rev.*, 2011, **111**, in press (DOI:10.1021/cr1002112).
7 J. Choi, A. MacArthur, M. Brookhart and A. S. Goldman, *Chem. Rev.*, 2011, **111**, in press (DOI:10.1021/cr1003503).
8 M. T. Whited and R. H. Grubbs, *Acc. Chem. Res.*, 2009, **42**, 1607.
9 A. Friedrich, M. Drees, J. Schmedt auf der Günne and S. Schneider, *J. Am. Chem. Soc.*, 2009, **131**, 17552.
10 W. H. Bernskoetter, C. K. Schauer, K. I. Goldberg and M. Brookhart, *Science*, 2009, **326**, 553.
11 L. Schwartsburd, M. A. Iron, L. Konstantinovski, Y. Diskin-Posner, G. Leitus, L. J. W. Shimon and D. Milstein, *Organometallics*, 2010, **29**, 3817.
12 D. Milstein, *Top. Catal.*, 2010, **53**, 915.
13 B. Gnanaprakasam, J. Zhang and D. Milstein, *Angew. Chem. Int. Ed.*, 2010, **49**, 1468.
14 C. Gunanathan, Y. Ben-David and D. Milstein, *Science*, 2007, **317**, 790.
15 C. Gunanathan, L. J. W. Shimon and D. Milstein, *J. Am. Chem. Soc.*, 2009, **131**, 3146.
16 B. Gnanaprakasam, Y. Ben-David and D. Milstein, *Adv. Synth. Catal.*, 2010, **352**, 3169.
17 W. H. Bernskoetter and M. Brookhart, *Organometallics*, 2008, **27**, 2036.
18 M. Albrecht, *Chem. Rev.*, 2009, **110**, 576.
19 (*a*) C. J. Moulton and B. L. Shaw, *J. Chem. Soc., Dalton Trans.*, 1976, 1020; (*b*) J. Dupont, N. Beydon and M. Pfeffer, *J. Chem. Soc., Dalton Trans.*, 1989, 1715.
20 P. Dani, M. A. M. Toorneman, G. P. M. van Klink and G. van Koten, *Organometallics*, 2000, **19**, 5287.

21 A. Vigalok, O. Uzan, L. J. W. Shimon, Y. Ben-David, J. M. L. Martin and D. Milstein, *J. Am. Chem. Soc.*, 1998, **120**, 12539.
22 X. Zhang, M. Kanzelberger, T. J. Emge and A. S. Goldman, *J. Am. Chem. Soc.*, 2004, **126**, 13192.
23 (*a*) M. H. G. Prechtl, M. Hölscher, Y. Ben-David, N. Theyssen, R. Loschen, D. Milstein and W. Leitner, *Angew. Chem. Int. Ed.*, 2007, **46**, 2269; (*b*) M. H. G. Prechtl, M. Hölscher, Y. Ben-David, N. Theyssen, D. Milstein and W. Leitner, *Eur. J. Inorg. Chem.*, 2008, **2008**, 3493.
24 W. H. Bernskoetter, S. K. Hanson, S. K. Buzak, Z. Davis, P. S. White, R. Swartz, K. I. Goldberg and M. Brookhart, *J. Am. Chem. Soc.*, 2009, **131**, 8603.
25 A. Y. Verat, M. Pink, H. Fan, J. Tomaszewski and K. G. Caulton, *Organometallics*, 2008, **27**, 166.
26 D. F. MacLean, R. McDonald, M. J. Ferguson, A. J. Caddell and L. Turculet, *Chem. Commun.*, 2008, 5146.
27 A. de Meijere and F. Diederich, eds., *Metal-Catalyzed Cross-Coupling Reactions*, 2nd edn., Wiley-VCH, Weinheim, 2004.
28 (*a*) A. J. Canty and G. van Koten, *Acc. Chem. Res.*, 1995, **28**, 406; (*b*) B. Rybtchinski and D. Milstein, *Angew. Chem. Int. Ed.*, 1999, **38**, 870.
29 D. H. Ess, W. A. Goddard and R. A. Periana, *Organometallics*, 2010, **29**, 6459.
30 M. Gandelman, A. Vigalok, L. Konstantinovski and D. Milstein, *J. Am. Chem. Soc.*, 2000, **122**, 9848.
31 (*a*) M. Gozin, A. Weisman, Y. Ben-David and D. Milstein, *Nature*, 1993, **364**, 699; (*b*) B. Rybtchinski, A. Vigalok, Y. Ben-David and D. Milstein, *J. Am. Chem. Soc.*, 1996, **118**, 12406; (*c*) M. E. van der Boom, S.-Y. Liou, Y. Ben-David, M. Gozin and D. Milstein, *J. Am. Chem. Soc.*, 1998, **120**, 13415; (*d*) M. E. van der Boom, H.-B. Kraatz, L. Hassner, Y. Ben-David and D. Milstein, *Organometallics*, 1999, **18**, 3873.
32 M. E. van der Boom, M. Gozin, Y. Ben-David, L. J. W. Shimon, F. Frolow, H.-B. Kraatz and D. Milstein, *Inorg. Chem.*, 1996, **35**, 7068.
33 B. Rybtchinski, R. Cohen, Y. Ben-David, J. M. L. Martin and D. Milstein, *J. Am. Chem. Soc.*, 2003, **125**, 11041.
34 B. Rybtchinski, S. Oevers, M. Montag, A. Vigalok, H. Rozenberg, J. M. L. Martin and D. Milstein, *J. Am. Chem. Soc.*, 2001, **123**, 9064.
35 B. Rybtchinski and D. Milstein, *J. Am. Chem. Soc.*, 1999, **121**, 4528.
36 R. M. Gauvin, H. Rozenberg, L. J. W. Shimon, Y. Ben-David and D. Milstein, *Chem. Eur. J.*, 2007, **13**, 1382.
37 (*a*) D. M. Grove, G. van Koten, J. N. Louwen, J. G. Noltes, A. L. Spek and H. J. C. Ubbels, *J. Am. Chem. Soc.*, 1982, **104**, 6609; (*b*) D. M. Grove, G. van Koten and H. J. C. Ubbels, *Organometallics*, 1982, **1**, 1366; (*c*) J. Terheijden, G. van Koten, I. C. Vinke and A. L. Spek, *J. Am. Chem. Soc.*, 1985, **107**, 2891; (*d*) P. Steenwinkel, H. Kooijman, W. J. J. Smeets, A. L. Spek, D. M. Grove and G. van Koten, *Organometallics*, 1998, **17**, 5411.
38 (*a*) M. Albrecht, R. A. Gossage, A. L. Spek and G. van Koten, *J. Am. Chem. Soc.*, 1999, **121**, 11898; (*b*) M. Albrecht, A. L. Spek and G. van Koten, *J. Am. Chem. Soc.*, 2001, **123**, 7233..
39 J. V. Ortiz, Z. Havlas and R. Hoffmann, *Helv. Chim. Acta*, 1984, **67**, 1.
40 M. Gandelman, L. J. W. Shimon and D. Milstein, *Chem. Eur. J.*, 2003, **9**, 4295.
41 M. Gozin, M. Aizenber, S.-Y. Liou, A. Weisman, Y. Ben-David and D. Milstein, *Nature*, 1994, **370**, 42.
42 (*a*) R. Cohen, M. E. van der Boom, L. J. W. Shimon, H. Rozenberg and D. Milstein, *J. Am. Chem. Soc.*, 2000, **122**, 7723; (*b*) R. Cohen, D. Milstein and J. M. L. Martin, *Organometallics*, 2004, **23**, 2336.
43 H. Salem, Y. Ben-David, L. J. W. Shimon and D. Milstein, *Organometallics*, 2006, **25**, 2292.
44 C. M. Frech, L. J. W. Shimon and D. Milstein, *Chem. Eur. J.*, 2007, **13**, 7501.
45 S.-Y. Liou, M. E. van der Boom and D. Milstein, *Chem. Commun.*, 1998, 687.
46 M. Gandelman and D. Milstein, *Chem. Commun.*, 2000, 1603.
47 E. Balaraman, B. Gnanaprakasam, L. J. W. Shimon and D. Milstein, *J. Am. Chem. Soc.*, 2010, **132**, 16756.
48 M. E. van der Boom, S.-Y. Liou, Y. Ben-David, L. J. W. Shimon and D. Milstein, *J. Am. Chem. Soc.*, 1998, **120**, 6531.
49 H. D. Empsall, E. M. Hyde, C. E. Jones and B. L. Shaw, *J. Chem. Soc., Dalton Trans.*, 1974, 1980.
50 C. E. Jones, B. L. Shaw and B. L. Turtle, *J. Chem. Soc., Dalton Trans.*, 1974, 992.
51 J. Yang, P. S. White and M. Brookhart, *J. Am. Chem. Soc.*, 2008, **130**, 17509.
52 (*a*) J. Yang and M. Brookhart, *J. Am. Chem. Soc.*, 2007, **129**, 12656; (*b*) J. Yang and M. Brookhart, *Adv. Synth. Catal.*, 2009, **351**, 175.
53 A. Vigalok, Y. Ben-David and D. Milstein, *Organometallics*, 1996, **15**, 1839; see also ref. 3*b*.
54 M. A. McLoughlin, N. L. Keder, W. T. A. Harrison, R. J. Flesher, H. A. Mayer and W. C. Kaska, *Inorg. Chem.*, 1999, **38**, 3223.
55 (*a*) W. C. Kaska, S. Nemeh, A. Shirazi and S. Potuznik, *Organometallics*, 1988, **7**, 13; (*b*) K.-W. Huang, J. H. Han, C. B. Musgrave and E. Fujita, *Organometallics*, 2007, **26**, 508.
56 E. Poverenov, I. Efremenko, A. I. Frenkel, Y. Ben-David, L. J. W. Shimon, G. Leitus, L. Konstantinovski, J. M. L. Martin and D. Milstein, *Nature*, 2008, **455**, 1093.
57 L. Schwartsburd, E. Poverenov, L. J. W. Shimon and D. Milstein, *Organometallics*, 2007, **26**, 2931.
58 B. E. Smart, in *The Chemistry of Functional Groups, Supplement D*, S. Patai and Z. Rappoport, eds., John Wiley & Sons, New York, 1983.
59 A. R. Fout, J. Scott, D. L. Miller, B. C. Bailey, M. Pink and D. J. Mindiola, *Organometallics*, 2009, **28**, 331.
60 L. Schwartsburd, R. Cohen, L. Konstantinovski and D. Milstein, *Angew. Chem. Int. Ed.*, 2008, **47**, 3603.
61 (*a*) Z. Huang, J. Zhou and J. F. Hartwig, *J. Am. Chem. Soc.*, 2010, **132**, 11458; (*b*) J. Zhao, A. S. Goldman and J. F. Hartwig, *Science*, 2005, **307**, 1080.
62 E. Khaskin, M. A. Iron, L. J. W. Shimon, J. Zhang and D. Milstein, *J. Am. Chem. Soc.*, 2010, **132**, 8542.
63 M. Findlater, W. H. Bernskoetter and M. Brookhart, *J. Am. Chem. Soc.*, 2010, **132**, 4534.
64 M. Feller, E. Ben-Ari, M. A. Iron, Y. Diskin-Posner, G. Leitus, L. J. W. Shimon, L. Konstantinovski and D. Milstein, *Inorg. Chem.*, 2010, **49**, 1615.
65 (*a*) S. W. Kohl, L. Weiner, L. Schwartsburd, L. Konstantinovski, L. J. W. Shimon, Y. Ben-David, M. A. Iron and D. Milstein, *Science*, 2009, **324**, 74; for a theoretical study, see: (*b*) X. Yang and M. B. Hall, *J. Am. Chem. Soc.*, 2010, **132**, 120.
66 S. J. Mitton, R. McDonald and L. Turculet, *Organometallics*, 2009, **28**, 5122.

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Cleavage of unreactive bonds with pincer metal complexes

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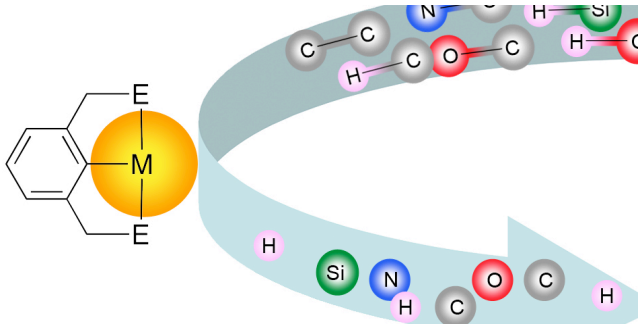
Due to the unique flexibility and tunability of pincer ligands, organometallic pincer complexes have been successfully employed for mediating and often also catalyzing the cleavage of typically unreactive bonds,