

Nickel and Palladium Complexes with Reactive σ -Metal-Oxygen Covalent Bonds.

Luis M. Martínez-Prieto^[a] and Juan Cámpora.*^[b]

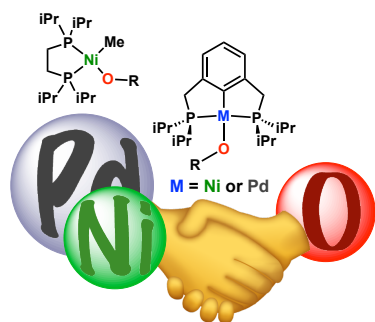
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Nickel and palladium complexes with terminal hydroxide, alkoxide and other covalently-bound metal-oxygen bonds exhibit a combination of organometallic type reactivity with strong basicity and nucleophilicity. This article reviews results from our research group in the context of the general literature.

Short Biographies



and amido complexes and their applications in homogeneous catalysis.

Juan Cámpora is CSIC Research Professor at the Institute for Chemical Research (IIQ, CSIC-University of Seville) since 2012. He graduated with honors in 1986 and took his Ph. D. degree in Chemistry in 1990 under the supervision of Prof. E. Carmona. He was awarded a Fulbright grant for postdoctoral position with Prof. S. L. Buchwald at MIT, where he worked on the chemistry of titanium and zirconium benzyne and metallacyclic complexes (1990-1992). In 1995 he became permanent researcher at the newly created IIQ, where he is research group leader. He has authored over 100 publications, and supervised 15 Ph. D. thesis. His scientific interests focus on the organometallic chemistry of transition elements, in special, late transition metal alkyl, alkoxo and amido complexes and their applications in homogeneous catalysis.



“Instituto de Tecnología Química (ITQ)” (Valencia, Spain) in the team of Prof. A. Corma.

Luis Miguel Martínez-Prieto received his PhD degree in Chemistry from the University of Seville in 2012, working at the IIQ under the supervision of Profs. J. Cámpora and P. Palma on Ni and Pd pincer complexes with alkoxide ligands. He then moved with Prof. B. Chaudret at the “*Laboratoire de Chimie de Coordination*” (LCC; CNRS) in Toulouse, France for a postdoctoral stay. His research focused on the synthesis of metal nanoparticles (MNPs). In 2015 he joined the lab of Prof. P. van Leeuwen at the “*Lab. de Physique et Chimie des Nano-Objets*” (LPCNO; INSA), exploring the use of MNPs as catalysts. In 2017, he was awarded with a “*Juan de la Cierva*” fellowship, that allowed him to start an independent career working on confined metal catalysts at the

Nickel and Palladium Complexes with Reactive σ -Metal-Oxygen Covalent Bonds.[†]

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Abstract. *This article reviews the chemistry of nickel and palladium complexes with terminally bound hydroxide and alkoxide ligands. The research carried out in our group is discussed in the context of the general literature. It is shown that suitable methods of synthesis, combined with the choice of adequate ligands allow the isolation of a range of stable complexes. This has enabled a detailed investigation of the chemical reactivity of the M-O bonds, once believed to be intrinsically weak. The elucidation of trends in thermodynamic stability and kinetic lability is the key for a better understanding the reactivity of this class of compounds, that combines typical organometallic patterns, like β -hydrogen elimination, with classic properties as bases and nucleophiles. Based on reversible acid-base exchange and CO₂ insertion reactions, we discuss how the polarity of the M-OR bonds influence their relative stability, their hydrolytic sensitivity and their tendency to react with electrophiles.*

Keywords: Nickel; Palladium; O-Ligands; β -Hydrogen Elimination; CO₂ fixation.

Introduction

According to the conventional definition, organometallic compounds are those that contain at least one covalent metal-carbon bond.^[1] However, the boundaries of Organometallic Chemistry are fuzzy.^[2] For example, hydride or dinitrogen complexes have always been regarded as pertaining to the organometallic domain, even if they are lacking any metal-carbon bonds. In contrast, many other molecular metal compounds, such as titanium(IV) alkoxides or amides, nickel(II) acetylacetonate or palladium(II) acetate, are regarded as inorganic

[†] Dedicated to Prof. S. L. Buchwald in the 25th anniversary of the first report on the aryl amination reaction.

coordination compounds, even though the metal is covalently bound to essentially organic ligands. Although some oxygen donors, like the above-mentioned acetylacetonate, or carboxylates are frequently found in many organometallic compounds, their role is usually passive, as “ancillary” or stabilizing ligands. Over the past decades, many studies have shown that many typical organometallic reactions, including reactions like migratory insertion, β -hydrogen elimination or reductive couplings, are not exclusive of M-C or M-H bonds, but can also be observed for a range M-Heteroatom bonds. These reactions of covalently bound heteroatom-based ligands mean a wide expansion of the Organometallic Chemistry panorama. Amongst the earliest and most conspicuous cases of "organometallic-type" reactivity stand late transition amides, hydroxides and alkoxides. This article focuses mainly on the reactivity of nickel and palladium complexes with terminal hydroxide and alkoxide ligands.

The terminal coordination mode of the M-OR bonds in alkoxides is in many regards analogous to σ -M-C bonds of classic organometallic complexes. Alkoxide and amide ligands abound in the chemistry of the early transition metals, either in simple (binary) derivatives or in complexes containing other ligands. When bonded to such metals, alkoxide and amide ligands are relatively unreactive and contribute to stabilize their complexes. However, on moving to the right along the *d* transition series, this class of ligands become less common.^[3] The reason is that, as the metal ions becomes more electron-rich and less electropositive, the M-alkoxo or M-amido linkages become more reactive, to the point that such complexes become increasingly difficult to isolate and characterize. Although late transition metal hydroxide and alkoxide species have been long known to be intermediates in catalytic processes, e. g. palladium-catalyzed Wacker olefin oxidation,^[4] or olefin alkoxycarbonylations,^[5] well-characterized alkoxides of metals of groups 9 to 11 were chemical oddities until relatively recent time. Most often, the techniques and strategies successfully applied in the early days of organometallic chemistry to the synthesis of organometallic compounds failed to produce stable alkoxides or amido complexes, and when they did, their isolation was hampered by their high sensitivity to moisture. In addition, amides, alkoxides and even the more stable hydroxide complexes exhibit a pronounced tendency to expel other ligands, giving polynuclear species, or even polymeric insoluble solids. In 1988, Bryndza and Tamm reviewed the chemistry of monomeric late transition metal complexes with terminal hydroxide, alkoxide and amide ligands.^[3a] Amongst these, just a few examples were true terminal alkoxides of the group 10 elements in their usual +2 oxidation state.

The difficulties found in the synthesis of mononuclear late transition metal alkoxides and other related compounds, like amides, was formerly attributed to the inherent instability of the covalent M-O or M-N interactions. In a first approach, this proposal was justified in the context of Pearson's hard and soft acids and bases (HSAB) theory,^[6] as a consequence of the mismatch

between the “soft” metal acids and “hard” bases containing N and O donor atoms. In contrast, soft carbon anions would be a better match for late transition metal ions, leading to more stable M-C bonds. This essentially qualitative HSAB argumentation collides with the widespread occurrence of many oxygen-based ligands traditionally regarded as “hard” (e. g. carboxylates, acetylacetonates, etc) in the coordination chemistry of late transition metals. A more subtle argumentation resorted to the theory repulsive metal-ligand nonbonding π interactions.^[7] According to this concept, whereas early transition metal alkoxides and amides are stabilized by π -donation from the electron pairs of the metal-bonded N or O atoms into the empty d orbitals of the metal, most d orbitals in late transition metals are filled, resulting in non-bonding, repulsive p - d orbital interactions. Such repulsions are alleviated if the lone pairs of the metal-bound heteroatom are delocalized by conjugation with ligand-based π^* orbitals, as in carboxylates or acetylacetonates, or by push-pull interactions involving other ligands with π -acceptor capacity that may be present in the same complex, like CO.^[7,8] Both lines of argumentation, HSAB and π p - d repulsions, have been used to justify the difficulty of preparing late transition metal complexes with strongly π -donor ligands, not only alkoxides or amides, but also fluoride, or oxo.^[9] However, the relevance of p - d repulsions in the thermodynamic stability of late transition metal-heteroatom bonds is now considered less important.^[10]

More than three decades passed since Bryndza and Tamm’s review was published and, since that time, the chemistry of late transition metal complexes with alkoxo, amido and other hard, π -donor ligands has developed intensively.^[11] The number of applications of the special “organometallic-like” reactivity of transition metal compounds with M-N or M-O bonds has experienced a continuous growth. Some prominent examples of these are the Buchwald-Hartwig aryl amination^[12] (now celebrating its 25th anniversary), the Suzuki-Miyaura reaction,^[13,14] reductive couplings of carbonyl and unsaturated compounds,^[15] reduction of carbonyl compounds,^[16] aerobic^[17] or acceptorless^[18] alcohol oxidation, hydrogen borrowing alkylation,^[19] or various dehydrogenative coupling reactions,^[20] just to cite a few of them. In parallel, an intense effort has been deployed to understand the fundamental aspects of reactive metal-heteroatom bonds, either as catalytic intermediates or as stoichiometric reagents. Research in this field has been one of the interests in our group for many years, focusing mainly on the chemistry of Ni(II) and Pd(II) complexes containing reactive metal-heteroatom bonds. Although not exclusively, most of our work has concentrated in the use of the chelating diphosphine 1,2-bis(diisopropylphosphino)ethane, and the ⁱPrPCP pincer ligand, shown in Figure 1. Both systems have in common the strong PⁱPr₂ donors, and the joint presence of M-C and M-O bonds, confined into *cis* and *trans* geometries, respectively. The recent interest on the substitutive uses of abundant metals from the first transition series instead of precious or scarce elements, has put additional interest on the comparison of the analogous chemistries of Ni and

Pd. These considerations moved us to present an account of our investigations on the topic of Ni and Pd complexes containing reactive metal-oxygen bonds.

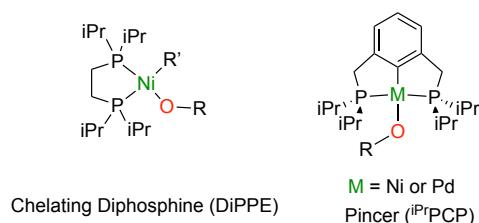
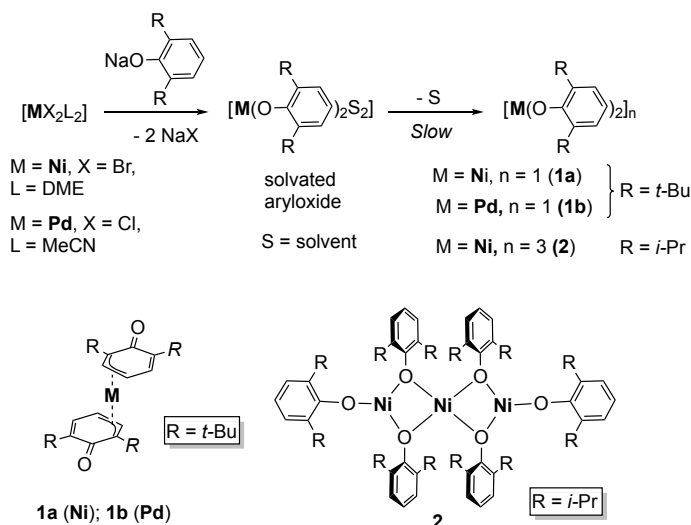


Figure 1. Basic structural types of nickel and palladium complexes with reactive M-O bonds studied in our laboratories.

Syntheses of nickel(II) and palladium(II) hydroxide and alkoxide complexes.

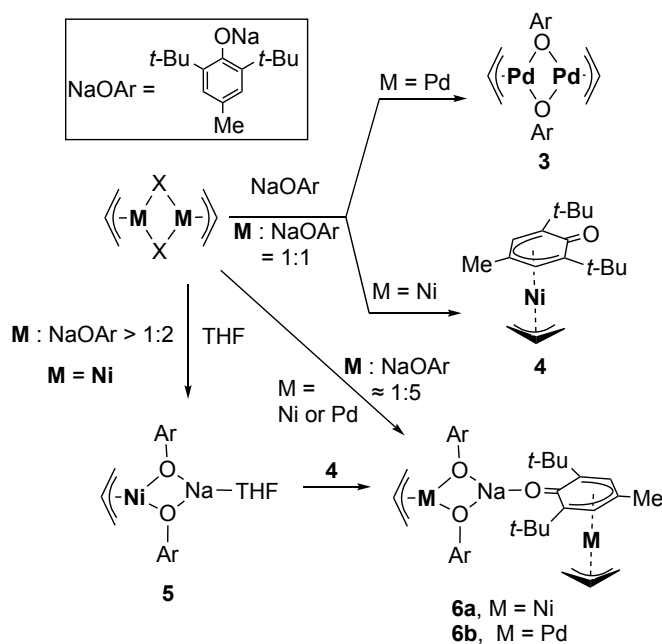
Out of the group 10 triad, Ni, Pd and Pt, only Ni gives rise to a simple hydroxide and alkoxide derivatives, $M(\text{OR})_2$. Nickel(II) hydroxide is a paramagnetic (high spin), polymeric solid formed by two dimensional layers of octahedra sharing their edges (CdI₂-type structure).^[21] At the turn of the past century, the literature just mentioned a few nickel alkoxides, obtained by metathetical exchange between nickel halides and alkaline alcoholates. These are insoluble solids of unknown structure,^[22] although a number of Ni and Pd hydroxide and aryloxide complexes stabilized by ancillary ligands were already known (see below). At the onset of our exploration of the chemistry of reactive alkoxides of Ni and Pd, one of our interests was to establish whether discrete species containing -OR ligands could be stabilized using bulky enough R groups. Therefore we investigated the reaction of $[\text{NiBr}_2(\text{DME})]$ (DME = 1,2-dimethoxyethane) and $[\text{PdCl}_2(\text{MeCN})_2]$ with sodium salts of phenols that had bulky substituents R in their ortho positions Scheme 1).^[23] For R = *t*Bu, diamagnetic aryloxides $M(\text{OAr})_2$ **1a** and **1b** were obtained in moderate yields, as deep -colored crystalline solids, respectively, soluble in hydrocarbon solvents. They have unusual π -sandwich structures, with the ligands interacting in η^3 mode (π -allyl-type) fashion through C2, C3 and C4, but not with the oxygen atom, therefore these compounds cannot be considered true aryloxides. However, solvated intermediates with a σ -type structure were also isolated.^[24] By lowering the steric hindrance of the ortho R groups, normal oxygen coordination becomes prevalent. Thus, for R = *i*Pr a black paramagnetic nickel compound **2** was obtained. Its X-ray diffraction structure reveals a linear array of three Ni atoms linked by four μ -OAr interactions, and two terminal terminal OAr ligands in the Ni atoms of the sides. These atoms are tricoordinated, a highly unusual environment for Ni(II). Complex **2** is a

true molecular Ni(II) alkoxide, and remains hitherto the only example of this class of compounds in the group 10 triad, although several monomeric (linear) Ni(II) amides were reported later.^[25]



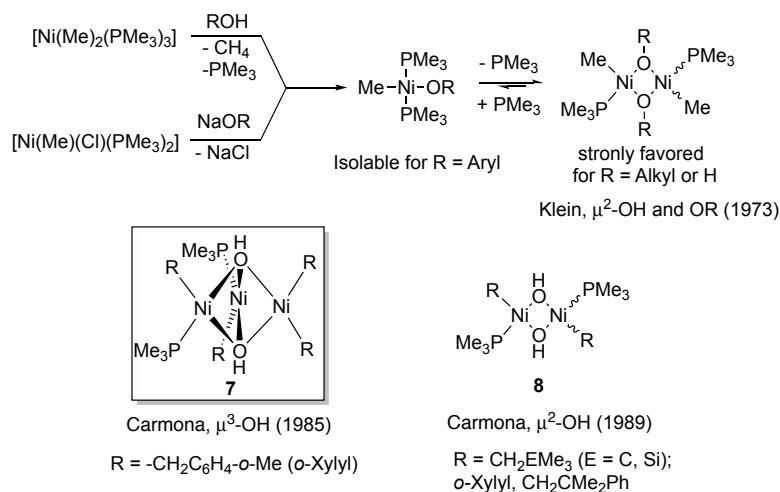
Scheme 1. Synthesis of binary Ni(II) and Pd(II) aryloxides with discrete molecular structures.

The unusual π -allyl-type coordination found in complexes **1** led us to investigate the synthesis of similar complexes containing a plain η^3 -C₃H₅ fragment as an ancillary ligand, hence we explored the reaction of the dimeric allyl complexes $[M(\eta^3\text{-C}_3\text{H}_5)(\mu\text{-X})_2]$ (M = Ni or Pd; X = Br or Cl) with sodium phenoxides containing differently sized aryloxide anions.^[26] For bulky aryloxides (*ortho* R = *t*Bu), signs of destabilization of the M-O bond were observed again. As shown in Scheme 2, the outcome of such reactions is highly dependent on the metal and the metal/aryloxide ratio. For a metal/NaOAr ratio = 1, and for M = Pd, the “normal” σ -aryloxide-bridged dimer **3** was produced, but this is thermally unstable and decomposes in solution giving free ArOH and black palladium. For M = Ni, a monomeric π -aryloxide complex $[Ni((\eta^3\text{-C}_3\text{H}_5)(\eta^5\text{-OAr}))]$, **4** was obtained. Increasing the Ni/NaOAr ratio led to the “ate” allyl-aryloxide complex **5**, solvated with a single molecule of THF. When this complex is mixed with an equimolar amount of **4**, the π -aryloxide fragment displaces the solvent to yield **6a**, another Ni-Na bimetallic complex with a Na atom linking σ - and π -Ni aryloxide units. **6a**, and its palladium analogue **6b** can be directly obtained by carefully adjusting the M:NaOAr ratio and the reaction time. Shortly after our reporting of these complexes, A. Klein and A. Dogan reported the crystal structure of a cationic palladium π -aryloxide, $[Pd(\eta^2:\eta^2\text{-COD})(\eta^5\text{-OC}_6\text{H}_2\text{Me}_3)]^+$.^[27]



Scheme 2. Syntheses of allyl-aryloxide complexes of Ni(II) and Pd(II).

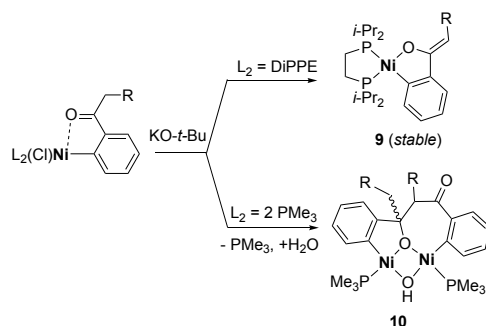
Simultaneously with these studies, we also investigated the syntheses of nickel complexes with terminal alkoxide, hydroxide or other potentially reactive σ -bound fragments, stabilized with suitable ancillary ligands. As mentioned above, a small number of molecular group 10 hydroxide and alkoxide complexes were known at this time. Most of them were Pd or Pt complexes, but very little was known about similar Ni derivatives. Scheme 3 summarizes some of the precedents on molecular Ni(II) hydroxides and alkoxides. The pioneering work of H. F. Klein with methylnickel complexes stabilized with monodentate PMe_3 ligands revealed that square-planar complexes of the type $[\text{Ni}(\text{Me})(\text{X})(\text{PMe}_3)_2]$ are stable if $\text{X} = \text{Cl}$, OCOR , or OAr , but not for $\text{X} = \text{OH}$ or OR .^[28] The latter compounds spontaneously lose one PMe_3 unit to afford dimers with $\mu\text{-OH}$ or $\mu\text{-OR}$ bridging ligands, because such interactions allow dissipating the excess of electron density localized at the oxygen atom. The trinuclear hydroxide **7** is another example of the tendency of basic OH ligands to share its electron density through bridging interactions is.^[29] The discovery of this complex in E. Carmona's group in the early 1980's led the Sevilla team to investigate the chemistry of nickel hydroxide complexes $[\text{Ni}(\text{R})(\mu\text{-OH})(\text{PMe}_3)_2]_2$ (**8**),^[29b] a work that, years later, inspired us to pursue the investigation of monomeric hydroxides and alkoxides of nickel and palladium. Similar arylpalladium hydroxides $[\text{Pd}(\text{R})(\mu\text{-OH})(\text{PPh}_3)_2]$ were reported by H. Alper and V. V. Grushin in 1993.^[30]



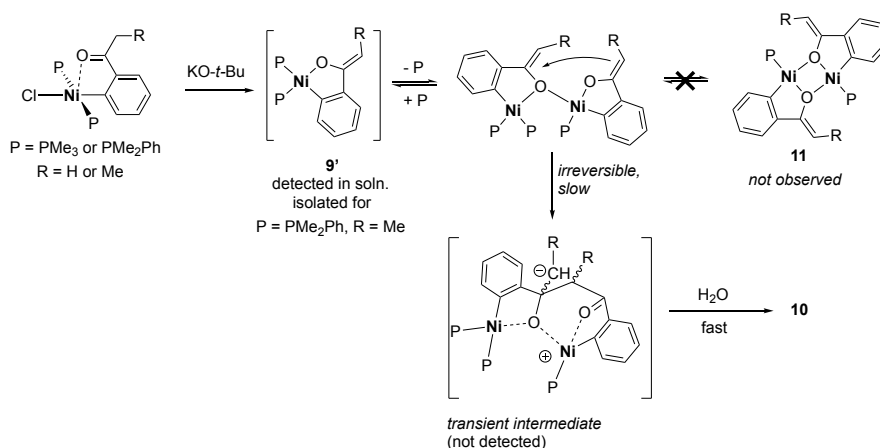
Scheme 3. Precedents in the chemistry of Ni(II) alkoxide and hydroxide complexes.

The tendency of basic, O-bound covalent ligands to bridge metal centers is very general and has deep effects in the properties of their complexes. For example, the bridging interaction partially cancels the reactivity on the O atom, but reversible M-OR dissociation can open a transient coordination site, providing low-energy pathways for processes such as β -hydrogen elimination,^[31] reductive coupling^[32] or migratory insertion.^[33] In some other cases, the association of reactive species gives results in more complex behaviors. We observed one such situation when attempting to prepare nickel enolate complexes. A metal can bind either the deprotonated carbon atom (C-enolates) or the oxygen of the enolate functionality (O-enolates). Each of these modes has its own, characteristic reactivity, the O mode behaving as a nucleophilic alkoxide, and the C-enolate as a stabilized metal alkyl, but the difference is usually masked by the facile exchange of both coordination modes. Thus, we decided to synthesize a rigid nickelacyclic enolate, in order to prevent the otherwise facile isomerization of the C and O-coordination modes.^[34] As shown in Scheme 4, we started from 2-acylaryl nickel complexes (acyl = acetyl or propionyl), and then carried out the deprotonation of the acyl group with potassium *t*-butoxide. Pre-activation of the acyl fragment by the Ni center, confirmed by X-ray structures, promotes selective formation of the O-bonded isomer, and the strong chelate DiPPE ensures the stability of the O-enolate complex, **9**. However, PMe_3 as ancillary ligand leads to the unusual binuclear complexes **10**. The formation of the latter can be rationalized as an aldol addition of an enolate unit across the acyl fragment of a second molecule of complex. In addition, it requires a molecule of water, that ends up in the bridging hydroxyl and the extra proton bound to the organic ligand. The mechanism of this reaction is shown in Scheme 5.^[35] When the substituent R on the enolate unit is Me, **9'** is fairly stable in solution, but it spontaneously evolves to the final product **10** if isolation is attempted. The extra molecule of water in **10** suggests that the product somehow arises from a hydrolysis reaction. However, the reaction is triggered by the loss of volatile PMe_3 , allowing the appearance of alkoxide bridge interactions, and water

merely captures the reactive intermediate arising from this process. Replacement of PMe_3 with the less volatile phosphine PMe_2Ph hinders the dimerization equilibrium, and for $\text{R} = \text{Me}$ the enolate is an isolable compound. Symmetric dimers like **11**^[33b] but were not detected in our system, because the initial stage of the association process brings about the irreversible C-C bond formation.^[36]



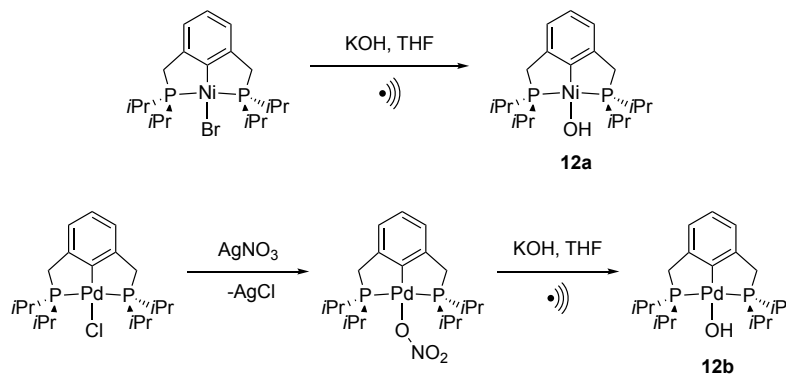
Scheme 4. Self-aldol reaction of nickel enolates promoted by bridging alkoxide interactions



Scheme 5. Dimerization-driven mechanism of the self-aldol reaction.

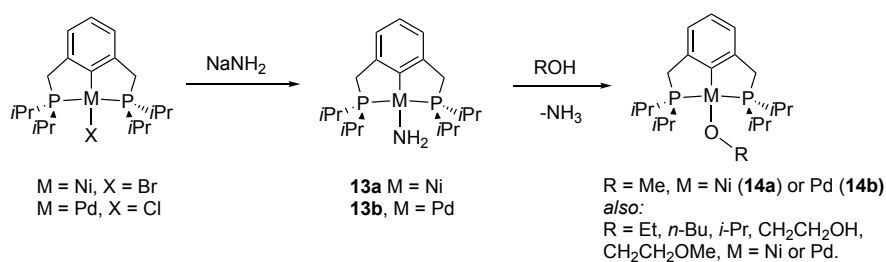
On continuing our investigation of the reactive M-O bonds of nickel and palladium, we decided to abandon the use of dissociable ligands in favor of DiPPE or the $i^{\text{Pr}}\text{PCP}$ pincer, shown in Figure 1, to enforce terminal coordination of O-ligands similar to σ -organometallic alkyls. Although pincer ligands, particularly that of the NCN type, were becoming usual in the chemistry of group 10 elements already in the 1990's, just a few nickel and palladium complexes with the PCP pincer framework had been reported.^[37] On the other hand, whereas a couple of monomeric Pd hydroxides supported by terpyridine^[38] or Tp ^[39] ligands had been reported, these were rare species that attracted much interest as biomimetic models for enzymes.^[3e] Thus, we investigated the reaction of precursors $[(i^{\text{Pr}}\text{PCP})\text{M}(\text{X})]$ with excess of KOH in THF, which afforded the first pincer-stabilized, monomeric hydroxides $[(i^{\text{Pr}}\text{PCP})\text{M}(\text{OH})]$ **12a** and **12b**. Both were fully characterized, including their X-ray structure determination (Scheme 6).^[40] For palladium, the Cl/OH exchange reaction is sluggish but becomes more facile if the starting material is converted previously in the nitrate derivative by exchange with AgNO_3 . In both cases,

the reactivity of solid KOH was enhanced by sonication using a regular ultrasounds cleaning bath.



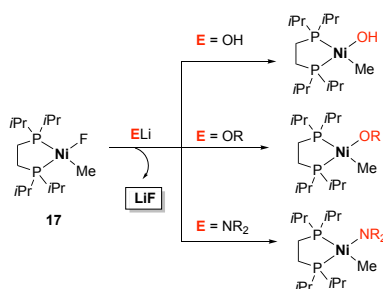
Scheme 6. Syntheses of some of group 10 hydroxide complexes with $i\text{PrPCP}$ pincer ligands.

Straightforward exchange of halide hydroxides or alkoxides with alkali metal reagents be complicated by side reactions. Phosphine ligands can be attacked by hydroxide, causing partial or complete reduction of the starting material,^[30,41] and strong bases can induce β -hydrogen elimination from alkoxide through not always well understood intermolecular mechanisms, particularly in the presence of free alcohols.^[42] The occurrence of undesired side processes is difficult to predict, as some systems withstand more successfully than others the exchange with basic/nucleophilic reagents.^[42-46] In our earliest attempts to prepare the Ni and Pd methoxides $[(i\text{PrPCP})\text{M}(\text{OMe})]$, we tried to proceed as with hydroxides **12**, but exchanging the precursor halide with sodium methoxide afforded mixtures due to incomplete conversion and competitive β -elimination,^[46] the hydrides $[(i\text{PrPCP})\text{M}(\text{H})]$ being identified among the products. A turnaround for this problem of competitive is selecting tertiary alkoxide groups without hydrogen atoms on the position next to oxygen, as *t*-butoxide,^[47,48] but the products can be very reactive and difficult to handle. Protic acid-base exchange reactions provide a milder and more general approach to the synthesis of alkoxide derivative. Alkoxide complexes are cleanly generated in solution when the corresponding hydroxides are treated with alcohols. Unfortunately, this reaction is synthetically unpractical, as the exchange are reversible equilibria, usually shifted to the side of the starting hydroxides.^[49] In contrast, similar the reaction of alcohols with amido complexes is often satisfactory, if such precursors are available. The parent amido complexes $[(i\text{PrPCP})\text{M}(\text{NH}_2)]$ (**13a**, M = Ni; **13b**, M = Pd) proved to be very convenient precursors for this purpose for the synthesis of the corresponding alkoxides, as they react quantitatively with a variety of alcohols to give the alkoxides (Scheme 7).^[50,51] The monomeric nickel amide, **13a**, can be isolated as a crystalline solid and, although its palladium analogue **13b** is unstable, it can be generated and used in solution. Thus, we developed a methodology to facilitate the generation of clean solutions of **13a** and **13b**, to be used *in situ*.^[49] This method allowed the isolation and structural characterization of a series of derivatives with common OR groups.

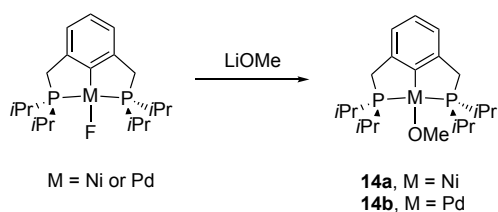


Scheme 7. General synthesis of Ni and Pd pincer alkoxides from parent amido precursors.

In comparison with amido complexes, late transition metal alkyls are usually unreactive towards such weak protic acids as alcohols. Although alkane elimination is a strong thermodynamic driving force, the lack of basic electron pairs on the C atom renders M-C bonds kinetically inert to protic acids, unless these are reasonably strong. A rare exception for this rule is Klein's highly reactive dimethyl nickel complex [NiMe₂(PMe₃)₃], which undergoes rapid and selective cleavage of a single Ni-Me bond by water, methanol or ethanol to afford the corresponding dimeric hydroxide or alkoxides (see Scheme 3).^[28] In contrast, nickel dialkyls stabilized with DiPPE are unreactive even with 2,6-dimethylphenol, a stronger acid than primary alcohols.^[52] Yet, [NiMe₂(DiPPE)] reacts selectively with many stronger acids, including trifluoromethanesulfonic acid, triethylammonium chloride or the mildly acidic salt triethylamine trihydrofluoride. In each case, the acid selectively cleaves only one Ni-Me bond, affording a series of complexes of composition [Ni(Me)(X)(DiPPE)], with X = OTf (**15**), Cl (**16**) and F (**17**).^[53] Thus fluoride **17** proved a very useful starting material for the syntheses of a range of alkoxide complexes. Thus, while the reactions of either **15** or **16** with alkaline hydroxides and alkoxides are incomplete and/or lead to mixtures of products, **17** reacts smoothly and quantitatively with LiOH, LiOR or LiNR₂, affording selectively the corresponding methyl-hydroxide, methyl-alkoxide and methyl-amido derivatives (Scheme 8).^[54] We believe that, rather than the arguable weakness of the Ni-F bond, the efficiency of these fluoride displacement reactions relates to the extra thermodynamic driving force provided by the elimination of LiF, one of the most stable and insoluble ionic solids. We later extended the range of application of the fluoride displacement methodology as an alternative method for the syntheses of ^{*i*}PrPCP-based nickel and palladium-alkoxo complexes (Scheme 9).



Scheme 8. Fluoride exchange with lithium reagents as an efficient method for the syntheses of nickel-heteroatom covalent bonds.



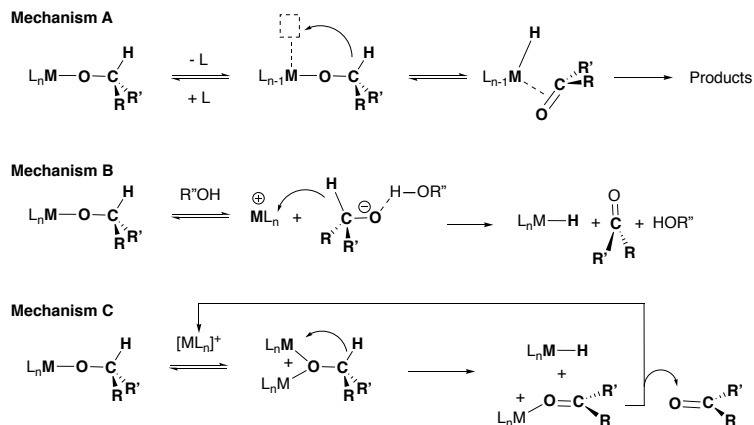
Scheme 9. Fluoride exchange with lithium methoxide as an alternative method for the synthesis of Ni and Pd alkoxides.

Thermal decomposition of alkoxide complexes of Ni and Pd.

Alkoxide complexes of late transition metals can undergo thermal decomposition through standard pathways analogous to those of σ -bonded organometallic compounds, such as reductive elimination or β -hydrogen elimination. These processes are key elemental steps in a number of catalytic processes for the transformation of alcohols and phenols into more complex organic molecules. Reductive elimination involving oxygen-bound ligands is unusual, even for a metal as prone to this as palladium.^[55] C-O reductive couplings from organo-Ni or -Pd alkoxides can be induced by oxidation, or from high-valent precursors in the less common oxidation states +3 or +4.^[56] In addition, bulky or wide-bite angle co-ligands can be tuned to favor C-O coupling from Pd(II).^[32,57]

The difficulty of C-O reductive eliminations is the cause of the lesser degree of development attained by palladium-catalyzed coupling of aryls and alcohols to ethers^[58] in contrast with the analogous C-N coupling in Buchwald-Hartwig aryl amination.^[12] On the contrary, β -hydrogen elimination is relatively frequent for alkoxides and constitutes the basis for a number of catalytic applications mentioned in the Introduction.^[17-20] Mechanistic studies have shown that β -hydrogen elimination may, in fact, involve different pathways, summarized in Scheme 10. Mechanism A is analogous to typical β -elimination in alkyl complexes, and requires a vacant coordination site in *cis* to the β -hydrogen donor ligand. Examples of this mechanism were revealed by the studies of Hartwig and Milstein on the decomposition of Ir(I), Vaska-type square-planar complexes, [*trans*-Ir(OCHRR')(CO)(PPh₃)₂]^[59,60] or octahedral Ir(III) alkoxides [*mer*-Ir(OMe)(Cl)(H)(PMe₃)₃]^[61] respectively. In both cases, the reaction begins with ligand dissociation and generation of a coordination vacancy. The first example involves dissociation a phosphine ligand, and a chloride anion the second. Surprisingly, octahedral d^6 Ir(III) alkoxo complexes that lack dissociable ligands in *cis* to the alkoxide can also experience solvent-assisted β -hydrogen elimination.^[42c] In this case mechanism B was proposed, in which the alkoxide ligand itself dissociates, and then the electrophilic Ir(III) fragment approaches the anion from the carbon side to perform a C-H bond activation. This mechanism has been invoked for other systems where the required coordination vacancy cannot be readily generated.^[42a,b]

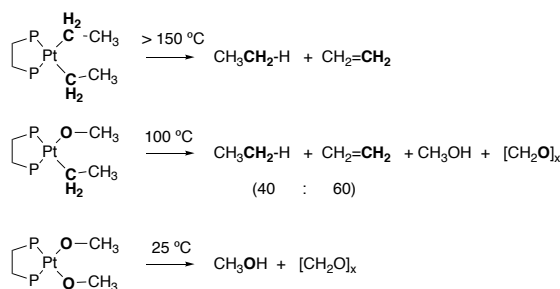
Bergman discovered that a third mechanism, C, can operate also in the decomposition of the Ir(III) complexes $[\text{Ir}(\text{OCH}_2\text{R})(\text{PMe}_3)(\text{Ph})(\text{Cp}^*)]$. The β -hydrogen abstraction is catalyzed by a small amount of the coordinatively unsaturated species, $[\text{Ir}(\text{PMe}_3)(\text{Ph})(\text{Cp}^*)]^+$ which, by binding the oxygen of the alkoxide, promotes the β -H elimination from the a bimetallic intermediate.^[62]



Scheme 10. Mechanisms for β -hydrogen elimination in late transition metal alkoxides.

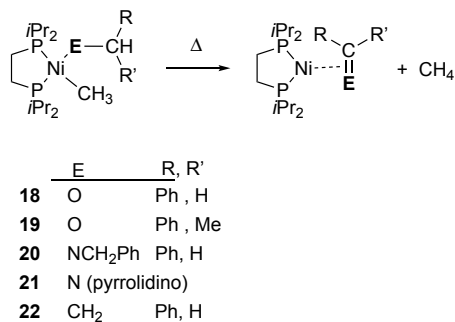
As pointed out in the Introduction, the paucity of alkoxides in the chemistry of the late transition metals was once attributed to the intrinsic instability of the metal-alkoxide linkage. Bryndza's mechanistic studies on the decomposition of well-defined Pt(II) methoxide complexes provided for the first time an insight on the relative ability of alkoxides and alkyls to decompose through the β -elimination pathway.^[63] As shown in Scheme 11, the products formed in the thermolyses of a series of related complexes containing ethoxide and ethyl ligands can be explained as the result of a single mechanism involving β -hydrogen elimination and reductive coupling. The β -hydrogen abstraction step was suggested to proceed through a mechanism of type A, with the axial coordination site available in these square-planar complexes providing the required *cis*-coordination vacancy, as Yamamoto suggested for the analogous decomposition of Pd(II) dialkyls.^[64] The structurally similar diethyl, ethyl-methoxy and dimethoxide derivatives decompose with increasing ease, as reflected on the decreasing temperatures required to induce the process. Apparently, these observations confirm that the methoxide ligand is intrinsically more prone to β -elimination than the ethyl. However, the ethane / ethylene ratio 40:60 produced in the decomposition of the mixed-ligand complex indicates that, *within the same compound*, the energy barrier for H transfer from methoxide is higher than from ethyl. A similar conclusion is reached when comparing the β -hydrogen elimination for Ir(I) Vaska alkoxides with the corresponding alkyl complexes: The alkoxides [*trans*-Ir(OCHR'R')(CO)(PPh₃)] are thermally robust, decomposing only above 80 °C, whereas analogous alkyl complexes (*i.e.*, with β -hydrogen atoms) are barely stable above 0 °C, rapidly undergoing β -elimination at higher

temperatures.^[60] Noteworthy, β -hydrogen elimination in related Vaska-type amido complexes takes place at temperatures comparable to those required by the alkoxides.^[65]

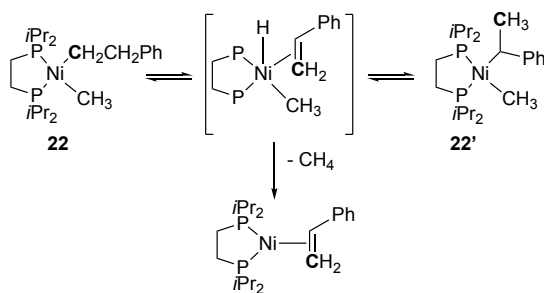


Scheme 11. β -hydrogen elimination coupled with irreversible reductive elimination in platinum complexes.

Our ability to synthesize a range of nickel alkoxide and amide complexes prompted us to examine the thermal stability of these complexes, in order gain some insight in their decomposition mechanisms. In one of our studies we compared the thermal stability of some methylnickel alkoxides and amides (**18** – **21**) available from the fluoride **17** (see Scheme 8).^[66] To complete this study, we included the mixed dialkyl **22**, also obtained through the mild fluoride exchange method. The decompositions of referred Ni compounds involves β -hydrogen abstraction and elimination of methane, as shown in Scheme 12. This is similar to the above-discussed Pt(II) system, except that the product are stable Ni(0) complexes with η^2 -aldehyde, ketone, imine and olefin ligands originated in the β -hydrogen abstraction step. A mechanistically relevant detail is that, during the preparation of **22** we observed the formation of the isomeric alkyl **22'** as a result of a "chain walking" process, as shown in Scheme 13. This demonstrates the reversibility of the β -hydrogen elimination step, at least for the alkyl case. Above the room temperature, **22** and **22'** attain the equilibrium situation within few minutes or seconds. Thus, reversible β -hydrogen elimination is much faster than the final reductive elimination, that becomes rate-determining.



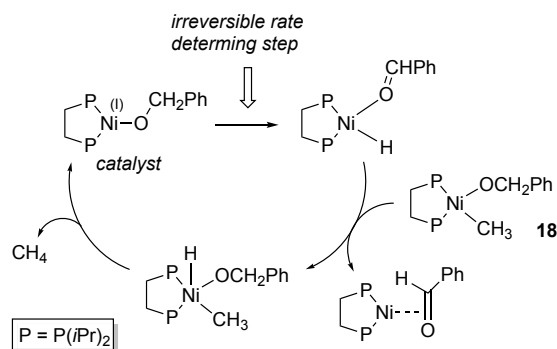
Scheme 12. Different β -hydrogen types of β -hydrogen transfer H-Me reductive elimination



Scheme 13. Reversible β-hydrogen pre-equilibrium in alkyl-methyl complexes.

An important difference between the Pt and Ni-based processes shown in Schemes 11 and 12 is that, whereas the former involves different H/OMe and H/Et couplings, all decompositions in the Ni system entail reductive elimination of methane in the final step. In consequence, any important kinetic differences in the decomposition rates of the Ni complexes could be attributed to the β-hydrogen elimination step. Therefore, a comparative kinetic study of the decay rate of the alkoxide, amido and alkyl complexes **18**, **20** and **22** was undertaken. As would be expected for an intramolecular mechanism like that shown in Scheme 13, the decomposition of alkyl **22** obeys first-order kinetics, characterized with a near-zero activation entropy ($\Delta S^\ddagger \approx 0$). The amide **20** follows also first-order kinetics, but with a large and positive ΔS^\ddagger . Therefore, both decompositions probably share essentially similar mechanisms, but these must have some significant difference. We believe that the positive activation entropy found for **20** might be the signature of pre-equilibrium step involving the opening of the diphosphine chelate ring, prior to the β-elimination and methane elimination.^[67] The activation enthalpies (ΔH^\ddagger) for the decomposition of **20** and **22** are 48 and 23 Kcal·mol⁻¹, respectively. Thus, discounted the entropy factor, the energy barrier for the decomposition of the amide is still higher for the amide than for the alkyl.^[68]

In contrast with **20** and **22**, the decomposition of alkoxide **18** shows a surprising zero-order kinetic dependency on the starting complex. In addition to point out to a totally different mechanism, the zero-order kinetics is puzzling because *apparently* there are no other components in the chemical system to control the reaction, that advances at a constant rate. This implies that there must be some undetected substance to exert the control of the reaction. Very likely, this catalyst must be some coordinatively unsaturated nickel complex, that promotes β-hydrogen elimination in the manner of Mechanism C (Scheme 10), but the lack of kinetic dependency on the starting material **18** implies that the rate is determined in an irreversible step that involves exclusively the catalyst. We suggested that the catalyst could be monomeric Ni(I) alkoxide that, on decomposing by β-hydrogen elimination (the rate-determining step), transfers the hydride to **18**, which then eliminates methane, as depicted in Scheme 14.

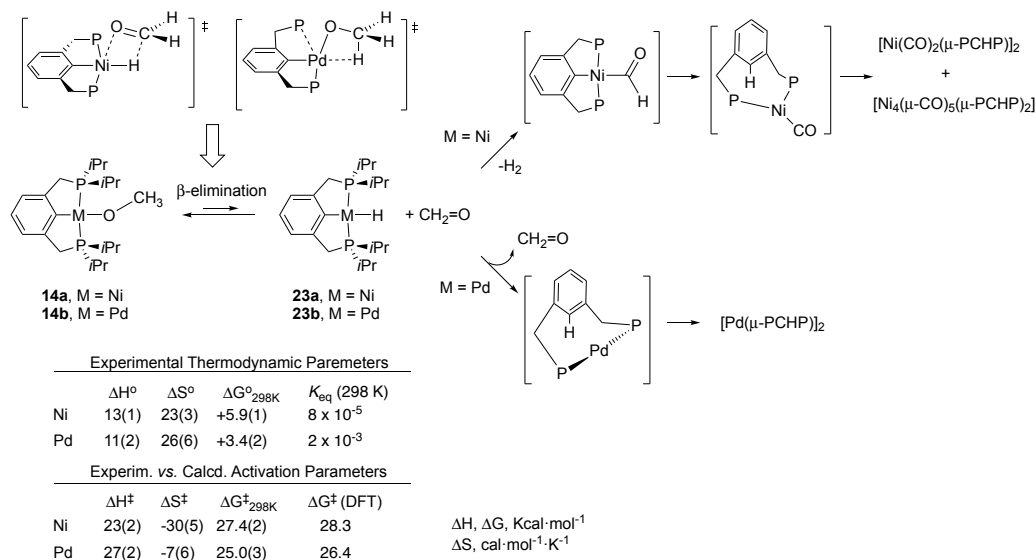


Scheme 14. Proposed mechanism for the decomposition of Ni(II) alkoxides catalyzed by Ni(I) species.

In line with the previously discussed investigations for Ir y Pt complexes, our conclusion is that the ease of β -hydrogen elimination methylNi(II) system decreases in the order alkyl > amide >> alkoxide. However, Fryzuk has reported a nickel system closely related to ours, [(^tBuPPC)Ni-ECHRR'], that contains a cyclometallated diphosphine ligand (^tBuPPC).^[69] In this system, β -hydrogen elimination for ECHRR' = alkyl, amido or alkoxide ligands, is followed by irreversible H transfer to the metallacycle, to give Ni(0) olefin, imino and ketone complexes, respectively. Fryzuk reports that attempts to introduce the alkoxo moiety led directly to the Ni(0) aldehyde complex, suggesting that β -hydrogen from the alkoxide is very fast, whereas the β -elimination from an amido ligand was considerably slower. However, since no mechanistic studies were carried out, any conclusions should be taken with caution.

We have also investigated the mechanism of the thermal decomposition of Ni and Pd methoxides with ⁱPrPCP pincer ligands, [(ⁱPrPCP)M-OMe] **14a** and **14b** (Scheme 15).^[51] Both complexes decompose in solution, through processes that involve β hydrogen elimination and H transfer to the pincer ligand to yield different M(0) species. The decomposition of the Pd methoxide **14b** is noticeable even at the room temperature, yielding formaldehyde and a binuclear Pd(0) complex, [(ⁱPrPCHP)Pd]₂, where ⁱPrPCHP stands for the demetallated "pincer" diphosphine. The Ni methoxide **14a** is stable in solution at the room temperature, but signs decomposition can be observed above 50 °C. In this case, the process entails full dehydrogenation of methoxide ligands to yield polynuclear Ni(0) carbonyl complexes with bridging ⁱPrPCHP ligands, along with H₂. Continuous monitoring of these decompositions in C₆D₆ allowed the detection of the Ni and Pd hydrides, **23a** and **23b** in the initial stages of the reaction. This was the first time that hydrides arising from β -hydrogen elimination were identified in the decomposition of well-defined alkoxides of Ni or Pd. Tests with authentic samples of the hydrides showed that, whereas the Pd complex **23b** decomposes yielding the same Pd(0) product as the methoxide, the Ni hydride **23a** is thermally robust, and the hydride does not migrate to the pincer ligand spontaneously. As represented in Scheme 15, the irreversible evolution of **23a** into a

nickel(0) carbonyl is brought about by formaldehyde, with loss of H₂. The identification of **23a** and **23b** enabled us to gather experimental thermodynamic and kinetic data for the β-elimination step, and compare with the results of DFT calculations.^[51b] The parameters shown in Scheme 15 confirm that both for M = Ni and Pd, β-elimination is reversible and slightly endothermic. This process is thermodynamically and kinetically more favorable for Pd than for Ni, but the activation barriers are similar, the difference being due to entropy effects. Two main conclusions were drawn from our mechanistic work on the decomposition of the Ni and Pd alkoxides **14a** and **14b**. First, the Pd alkoxide decomposes more readily than its analogue of Ni; the second is that for both metals, β-hydrogen elimination is reversible, and the equilibrium is slightly disfavored. In order to advance, reversible β-H elimination has to be connected to the irreversible decomposition of the hydrides **23a** and **23b**. This is facile for Pd, but for Ni requires a further reaction with formaldehyde to advance. Thus, the different stability of the methoxides of Ni and Pd is more connected to the behavior of the hydrides **23** than to the β-hydrogen elimination step itself. It is the reactivity of the hydrides **23** which largely determines the fate of the initial alkoxides **14**. This is probably more the general rule than an exception in the chemistry of late transition alkoxides, and helps explaining the critical role that the choice of reagents, solvents and, in general, the experimental conditions have for the success of their isolation as stable compounds.

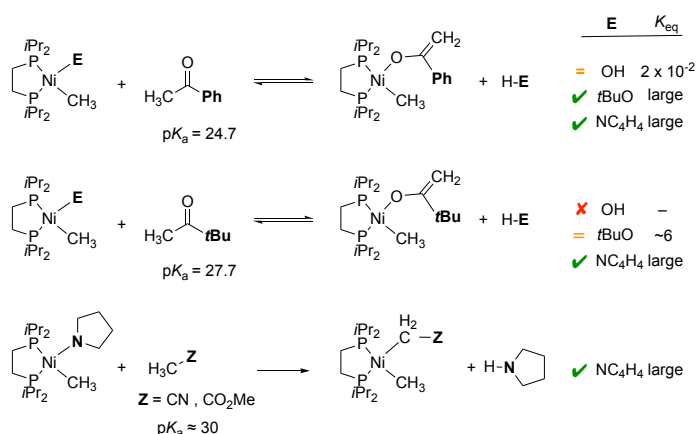


Scheme 15. Mechanism of decomposition and activation parameters for β-hydrogen elimination from methoxide in Ni and Pd pincer complexes.

Basicity and hydrolytic sensitivity.

One of the most characteristic features of late transition metal alkoxides and related compounds, is their facile hydrolysis, even with moisture traces. The hydrolytic sensitivity poses, in practice, one of the main difficulties for their isolation as pure species.

The reaction of the monomeric methylnickel hydroxide, *t*-butoxide and pyrrolidinide with enolizable ketones shown in Scheme 16 provides a good example of this type of reactivity.^[53c] The hydroxide complex reacts reversibly with the relatively acidic acetophenone ($pK_a \approx 24.7$ in DMSO), giving the corresponding *O*-enolate, but fails to deprotonate the less acidic ketone pinacolone ($pK_a = 27.7$ in DMSO). The *t*-butoxide complex reacts quantitatively with acetophenone. It also does with pinacolone, but the reaction is sluggish and slowly approaches an equilibrium situation. In contrast, the pyrrolidinide, an aliphatic amide, not only deprotonates rapidly and quantitatively both ketones, but also weaker carbon acids like ethyl acetate or acetonitrile ($pK_a = 30 - 31$ in DMSO). It is worth mentioning that protonation of the methyl group was never observed, even though the methide anion is a much stronger base than amides or alkoxides.



Scheme 16. Reaction of methylnickel hydroxide, alkoxide and amides with methylketones

It is illustrative to compare in some more detail the basic reactivity of the hydroxide and the *t*-butoxide complexes of Scheme 16. The constants for the equilibria between the hydroxide and acetophenone, and the *t*-butoxide and pinacolone are 0.02 and ≈ 6 , respectively. Considering that these values and the pK_a data of both ketones in DMSO, it is possible to estimate the equilibrium constant for the reaction of the *t*-butoxide with acetophenone as $\approx 6 \times 10^3$. This would be about five orders of magnitude higher than that the equilibrium constant for the hydroxide with the same ketone. This difference is much larger than one would expect from the basicities of the hydroxide and *t*-butoxide anions. Furthermore, in organic solvents, the hydroxide anion is actually a *significantly stronger base* than *t*-butoxide, as can be deduced from the pK_a 's of water

and *t*-butanol in DMSO, 31.2 and 29.4, respectively. Thus, the apparent basicities of the *t*-butoxide and hydroxide complexes would require some explanation. These are some: *i*) The *t*-butoxide complex is sterically destabilized as compared to the hydroxide, which renders the former more reactive; *ii*) the Ni-O bond in the hydroxide is significantly more stable than the *t*-butoxide; and *iii*) a combination of *i*) and *ii*). In order to provide a deeper insight in the acid-base relationships of alkoxide complexes of Ni and Pd, we examined water / alcohol proton exchange equilibria involving pincer hydroxo complexes **12a** or **12b** and several common alcohols, with not too different molecular sizes: methoxide, ethoxide, butoxide, 2-methoxyethoxide and *i*-propoxide, as shown in Scheme 17.^[49]

The water / alcohol exchange equilibrium constants (K_{ex}) were determined in dry C_6D_6 by titration of the hydroxides **12a** or **12b** with the alcohols. As can be seen, the equilibria are strongly shifted to the side of the hydroxide. This is consistent with the high hydrolytic sensitivity of the alkoxides, whose tendency to react with traces of water represents one of the major difficulties for the isolation and handling of pure samples of this type of compounds. The equilibrium constants for Ni are about one order of magnitude smaller than those of Pd, implying that nickel alkoxides are more sensitive to hydrolysis than those of palladium. This may be counterintuitive, because Pd alkoxides tend to be less stable and more difficult to isolate.

$$[(i^{\text{Pr}}\text{PCP})\text{M}-\text{OH}] + \text{ROH} \xrightleftharpoons[\text{C}_6\text{D}_6]{K_{\text{ex}}} [(i^{\text{Pr}}\text{PCP})\text{M}-\text{OR}] + \text{H}_2\text{O}$$

M = Ni, **12a**
M = Pd, **12b**

ROH	$\text{p}K_{\text{a, ROH}}$ (DMSO)	K_{ex}	
		M = Ni	M = Pd
H_2O	27.5	1	1
$\text{MeO}(\text{CH}_2)_2\text{OH}$	26.5	5.7×10^{-3}	5.0×10^{-2}
MeOH	27.9	1.6×10^{-2}	4.5×10^{-2}
EtOH	28.2	1.4×10^{-3}	2.6×10^{-2}
<i>i</i> PrOH	27.9	$\sim 3 \times 10^{-4}$	<i>n. d.</i>

Scheme 17. Alcohol-water exchange equilibria involving Ni and Pd pincer complexes.

At first glance, the trends shown in Scheme 17 are consistent with a "common sense" view. Since alcohols are usually seen as much weaker acids than water, they would not be expected to protonate a hydroxide to a large extent. As discussed in the preceding example, the difficulty with this reasoning is that H_2O is actually a much weaker acid in nonprotic organic solvents than it is as bulk liquid water. According to the $\text{p}K_{\text{a}}$'s listed in Scheme 17 water behaves in DMSO as an acid of comparable force or, in some case even weaker, than alcohols. Thus, it could be expected that the equilibria shown in Scheme 17 should be more shifted to the right than they appear in our experiments. However, such an interpretation misses the fact that we are not dealing with H^+ transfers between a neutral alcohol and a free OH^- anion (or, conversely, between water and OR^-), but exchanges between electroneutral, covalent species. Therefore, in order to give a correct interpretation to the values of K_{ex} , or, what is the same, the

corresponding $\Delta G^\circ_{\text{ex}}$, it is necessary to evaluate not only the proton transfer capacities of the alcohol and water, but also the strengths of the M-OH and M-OR bonds.

A simple approach to analyze neutral exchanges like those of Scheme 17 is to compute the reaction energy as the algebraic sum of the bond energies (or D_{bond}) that are being formed and broken. In these exchanges, M-OH and RO-H bonds break to form new M-OR and H-OH bonds (Eq 1). In this expression it is assumed that the entropy variation for the exchange is negligible, therefore $\Delta G^\circ_{\text{ex}} \approx \Delta H^\circ_{\text{ex}}$. Eq. 1 can be reorganized as shown in Eq. 2, and the differences within brackets can be regarded as "relative bond energies" (ΔD) in scales referred to $D_{\text{M-OH}}$ or $D_{\text{H-OH}}$, these becoming the common reference values. As the data for H-O bonds can be obtained from the literature, or computed by theoretical methods, the experimental $\Delta G^\circ_{\text{ex}}$ provide an estimate of the $\Delta D_{\text{M-OR}}$ values, *i. e.* the gauge for M-OR bond strengths that was being sought. These $\Delta D_{\text{M-OR}}$ are more susceptible of interpretation than the crude K_{ex} constants.

$$\Delta G^\circ_{\text{ex}} \approx \Delta H^\circ_{\text{ex}} = D_{\text{M-OR}} + D_{\text{H-OH}} - D_{\text{M-OH}} - D_{\text{H-OR}} \quad (1)$$

$$\Delta G^\circ_{\text{ex}} \approx (D_{\text{M-OR}} - D_{\text{M-OH}}) - (D_{\text{H-OR}} - D_{\text{H-OH}}) = \Delta D_{\text{M-OR}} - \Delta D_{\text{H-OR}} \quad (2)$$

In a pioneering work by Bryndza and Bercaw,^[70] this type of analyses was applied to exchanges between hydroxide or alkoxide complexes of Ru and Pt with various weak acids, HA (including not only alcohols). These authors found that the constants for such equilibria were close to unit, hence $\Delta G^\circ \approx 0$. Thus, according to Eq 2, the relative metal-ligand bond energies (in this case, $\Delta D_{\text{M-A}}$) approximately equal to the corresponding values of $\Delta D_{\text{H-A}}$. The conclusion is that, in these particular systems, the metal fragment "senses" the effect of the in the same way the influence of R, or in a graphic image, that the Ru and Pt centers behave as "large hydrogens". However, later work by Andersen, Bergman, and Holland on similar protic exchange reactions on Cp-Ni anilido complexes with HA acids showed that the thermoneutral condition ($\Delta G^\circ \approx 0$) is *not* a general feature of this type of exchange reactions.^[71] The degree of departure from the thermoneutral condition depends largely on the metal fragment considered. A survey of constants for the exchange equilibria of various late transition metal hydroxide complexes with methanol gave values spanning over three orders of magnitude.⁴⁹ Such deviations can be rationalized in terms of the different degree of polarization of the M-ligand bond and H-ligand bonds.^[71,72] In Pauling's classic description of the energies of polar covalent bonds, these have a significant covalent and ionic contributions, the latter a Coulombic attraction force between the charged fragments. The sum of the two components give rise to the overall bond energies. Accordingly, it has been shown that relative metal-ligand bond stabilities are satisfactorily fitted

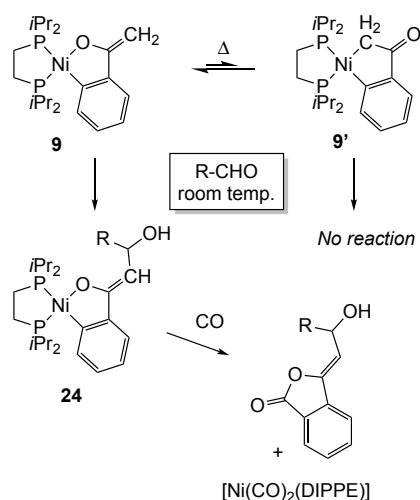
with Drago's empirical *E-C* model that accounts for both the electrostatic and covalent contributions of the bond.⁷¹

The analyses of the spectroscopic and structural features on Ni and Pd hydroxides and alkoxides [(*i*PrPCP)M(OH)] and [(*i*PrPCP)M(OR)] confirm that the M-O bond is strongly polar, to the point that they can be regarded as partially ionic.⁴⁹ Based on ¹³C NMR data for the [(*i*PrPCP)M] moiety, we deduced that the σ -donor capacity of the hydroxide and alkoxide groups is very similar, hence that the covalent bond energy is relatively independent of R and nearly the same for hydroxides and alkoxides. Thus, the effect of the R groups of alkoxides on the K_{ex} values is mostly due to electrostatic effects. Whereas the attractive force between the cationic metal fragment and the small and electronegative hydroxide ligand is particularly strong, the effect of large, polarizable R groups is to disperse the negative electric charge concentrated on the oxygen atom, reducing the magnitude of electrostatic attraction. The consequence is that, being the M-OR bonds are destabilized by R to a larger extent than the H-OR bonds, the difference $\Delta D_{\text{M-OR}} - \Delta D_{\text{H-OR}}$ is always positive ($\Delta G^{\circ}_{\text{ex}} > 0$), and the water / alcohol exchanges are shifted to the side of the hydroxide. The effect is larger for the R groups with a larger capacity to disperse the charge (e. g., the *i*Pr). This concept provides a rationale to the experimental order of the hydroxide-alcohol exchange constants, and also explains the fact that the effect of the R groups is more marked for Ni than Pd. This can be attributed to the smaller size of the Ni, and its slightly more electropositive character as compared to Pd.

Nucleophilicity and insertion chemistry.

In addition to their characteristic basicity of hydroxides and alkoxide complexes, the strong polarization of the metal-oxygen bond induces a significant nucleophilicity that results in a rich chemical reactivity. The role of bond polarization is especially evident in the case of enolate complexes. These can exist as either C-bound and O-bound isomers, each of which should exhibit a characteristic reactivity. The C-enolate should behave as alkyl alkyl, and the O-enolate is a special type of alkoxide. The effect of the coordination mode would be noticed if the chemical reactivity of the isomers could be probed independently, but the difference is usually masked due to the facile C/O exchange. As mentioned before, we have studied a series of nickel metallacyclic O-enolates, **9**, stabilized with the chelating diphosphine DiPPE. Nickel O-enolates are competent nucleophiles that selectively react with aldehydes, enones, or CO₂.^[34,53b,73] As shown in Scheme 18, the cyclic structure of the complex restricts C/O isomerization. This takes place only when **9** is heated in solution above 50 °C, with the thermodynamic isomer ratio becoming frozen when the solutions are rapidly cooled to the room temperature. When an aldehyde is added to a mixture of the O- and C- enolates, only the O-enolate isomer reacts with

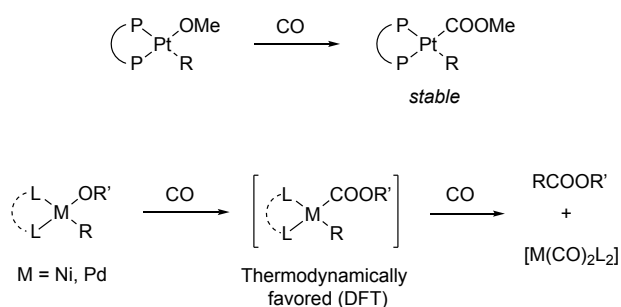
aldehydes, leaving the C-isomer unreacted.^[34] Due to the charge delocalization on the enolate functionality, the attack takes place invariably at the remote and less hindered CH₂ site. In general, the nucleophilic reactivity of this type of enolate complexes can be assimilated to that of a conventional carbon nucleophile, hence it shall not be discussed here in detail. An exception is the reaction of the enolates with carbon monoxide, as it does take place at the metal site. CO becomes incorporated in ester-type products, because insertion comes immediately followed by reductive ring closure, as shown in Scheme 18.



Scheme 18. Differential reactivity of isomeric O- and C-bound enolates with aldehydes

Reductive elimination is a common outcome for the carbonylation of Ni or Pd complexes that simultaneously contain M-C and M-O bonds. For example, alkyl-aryloxides of the type $[Ni(R)(OAr)(DIPPE)]$ react with CO to afford the corresponding esters $RCOOAr$ and $[Ni(CO)_2(DIPPE)]$.^[52] This sort of reactivity conceals the actual insertion site of CO, and prevents establishing whether it takes place into the Ni-O or the Ni-C bonds. CO insertion into Pd-OR bonds has been known for a long time to be involved in the catalytic carbonylations.^[74,75] Stable Pt(II) alkoxy carbonyl complexes ($L_nM-CO-OR$) arising from CO insertion into Pt-OR bonds were isolated by Bennett,^[76] Michelin^[77] and Bryndza^[78] in the 1970's and 80's. Carbonylation of complexes containing both Pt-C and Pt-OR groups invariably yields the alkoxy carbonyl products arising from CO insertion into the Pt-O rather than the Pt-C bonds (Scheme 19). Stable Pd(II) alkoxy carbonyl complexes bearing inert C_6F_5 groups resist reductive elimination. These were obtained from the reaction of hydroxide complexes with CO in alcohol solvents.^[79] Computational (DFT) analysis of the mechanism of CO insertion in simplified Group 10 models of the type $[M(Me)(OMe)(PH_3)_2]$ ($M = Ni, Pd, Pt$) confirmed that CO insertion into the M-OMe bonds proceeds through the migratory mechanism.^[80] Insertion in the M-OMe bond is thermodynamically favored over the M-CH₃, although the balance in favor of the M-OMe insertion decreases in the order $Pt (12 \text{ Kcal}\cdot\text{mol}^{-1}) > Pd (7 \text{ Kcal}\cdot\text{mol}^{-1}) > Ni (3 \text{ Kcal/mol})$. The

energy barriers for CO insertion, either in the M-C or M-O bonds are significant only for Pt, and much lower for Pd and Ni. For Pt and Pd, CO insertion into the M-O bonds is both thermodynamically and kinetically favored over M-C, but for Ni, the kinetic preference is reversed. However, the size of the energy barriers for Ni is so low that the kinetic control probably would be overridden by the thermodynamic preference, were the insertion product stable enough to be detected. The preference for the carbonylation of the alkoxide linkage arises largely from the formation of the particularly stable C(O)-OMe bond, that is largely independent of the metal. The strength of the ester-type C-O bonds is due to the interaction of the oxygen lone pairs with the empty π^* orbital of CO. This interaction is already present in the transition state of the migratory insertion (Figure 2), where it contributes to lower the energy barrier in comparison to the M-C insertion, that lacks this stabilizing factor. Independently of the participation of the oxygen electron pairs, the carbonylation mechanisms of M-OR bonds in square-planar d^8 metal complexes resembles the situation for similar alkyls, clearly favoring an associative pathway with a 5-coordinate carbonyl intermediate for Ni, and 4-coordinate intermediates for Pd and Pt.^[80] Further DFT studies on more realistic $[\text{Ni}(\text{Me})(\text{OR})(\text{HN}=\text{CHCH}=\text{NH})]$ and $[\text{Pt}(\text{Me})(\text{OR})(\text{PH}_2\text{CH}_2\text{CH}_2\text{PH}_2)]$ as models confirmed the main predictions from the above study and showed the influence of the O-R group on the thermodynamic balance of the reaction, the carbonylation of the M-O bonds becoming thermodynamically disfavored when OR is an aryloxy group.^[81]



Scheme 19. Experimental and theoretical preference for CO insertion in group 10 alkyl-alkoxo complexes

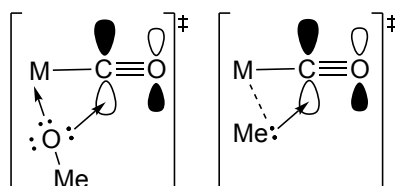
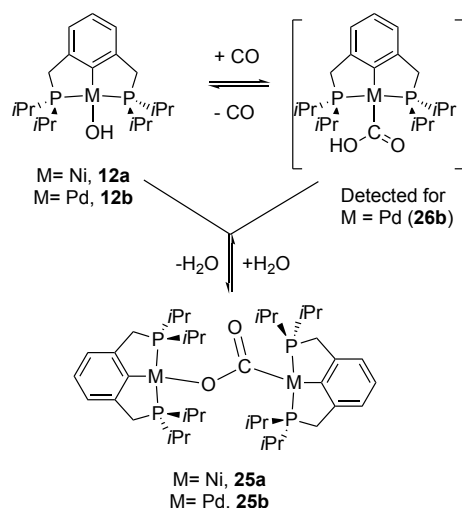


Figure 2. Transition states for the migratory insertion of CO into M-OMe and M-Me bonds.

The widespread application of pincer ligands in the 1990's opened new opportunities in the study of the fundamental reactivity of Ni-OR and Pd-OR bonds. When we synthesized the first monomeric Ni and Pd hydroxides with the ⁱPrPCP ligand (**12a** and **12b**), we were eager to investigate their reactivity towards small unsaturated molecules that typically undergo insertion reactions, CO in particular (Scheme 20).^[40] We found that both complexes react rapidly with bubbling CO at the room conditions, but only the Pd gave a straightforward result. The product was isolated and structurally characterized as the binuclear complex **25b**, that contains two [(ⁱPrPCP)Pd] units linked by a bridging -C(O)O- ligand (another way to see this ligand is as [CO₂]²⁻ a doubly reduced CO₂ molecule). The formation of this product can be rationalized as the result of the insertion of CO into the M-OH bond to afford a hydroxycarbonyl (M-COOH) species, **26**. The latter behaves as an acidic "metalacarboxylic" acid, and reacts with one equivalent of the starting hydroxide to yield the binuclear product. The nickel analog, **25a**, was obtained by careful reaction of **12a** with the precise stoichiometric amount of CO (*i. e.*, 0.5 equiv) in hexane, from which it precipitates. It was found that a larger amount of CO causes it to decompose into a mixture of unidentified products. More recently, Lee^[82] and Zargarian^[83] have reported that similar reactions of pincer-Ni hydroxide or siloxide complexes with CO lead to mixtures. Coming back to the reaction of the Pd hydroxide **12b** with CO, full carbonylation of the Pd-OH bonds is enforced under 3 bar of CO. When this is carried out in a thick-walled NMR tube, the hydroxycarbonyl complex **26b** was formed and was spectroscopically characterized *in situ*. However, upon CO removal **26b** reverts to the binuclear μ -CO₂ species **25b**, which implies the reversibility of CO insertion.



Scheme 20. Carbonylation of hydroxide pincer complexes **12a** and **12b**.

The hydroxycarbonyl chemistry supported by the ⁱPrPCP pincer contrasts with the straightforward results described by Wendt for the carbonylation of the closely related hydroxide

complexes $[(^t\text{BuPCP})\text{PdOH}]$ and $[(^t\text{BuPOC}_{\text{sp}^3}\text{POP})\text{NiOH}]$, both containing bulkier pincer ligands with $\text{CH}_2\text{P}(^t\text{Bu})_2$ side arms.^[84] These hydroxides react with CO to yield hydroxycarbonyl complexes that show no tendency to revert to the corresponding CO_2 -bridged dimers. In contrast, $[(^t\text{BuPCP})\text{PdCOOH}]$ releases CO_2 , affording the hydride $[(^t\text{BuPCP})\text{PdH}]$. If the reaction is carried out in a closed container, CO_2 can undergo “normal” insertion into the Pd-H bond resulting in overall isomerization of hydroxycarbonyl to formate $[(^t\text{BuPCP})\text{PdOC(O)H}]$. CO_2 extrusion is the usual decomposition pathway for metal hydroxycarbonyl species, and a critical step in the catalytic cycle of the water gas shift reaction (WGS).^[85]

Likely, the different behavior of the $i^{\text{Pr}}\text{PCP}$ and $^t\text{BuPCP}$ system originate from the large steric hindrance of the latter, that prevents the coupling of two pincer units into a CO_2 -bridged binuclear complex on the type **25**. The dimer was not formed even when the hydroxycarbonyl $[(^t\text{BuPCP})\text{PdCOOH}]$ was deliberately confronted with the hydroxide $[(^t\text{BuPCP})\text{Pd-OH}]$. Noteworthy, Y. Lee has reported an example of one such “neutralization” reaction with Ni, using an anionic PNP pincer system.^[82] This author reported that an hydroxycarbonyl complex, $[(\text{PNP})\text{Ni-COOH}]$, is formed in the carbonylation of the corresponding hydroxide $[(\text{PNP})\text{Ni-OH}]$. The $[(\text{PNP})\text{Ni-COOH}]$ complex proves acidic enough to be deprotonated with $\text{NaN}(\text{TMS})_2$, and also reacts with one extra equivalent of the hydroxide to afford the corresponding $\{[(\text{PNP})\text{Ni}]_2-\mu\text{-CO}_2\}$ species. Later, Lee reported that a Ni(I) pincer species $[(^{\text{acri}}\text{PNP})\text{Ni}\cdot]$ containing a modified PNP pincer reacts directly with CO_2 to afford the corresponding CO_2 -bridged binuclear complex.^[86] The reductive pathway to $\text{Ni}_2-\mu\text{-CO}_2$ complexes, combined with the above-mentioned reversibility of CO insertion, points at the potential application of Ni pincer hydroxides for the reduction of CO_2 to CO, reverting the WGS reaction. Reverse WGS is a critical step for using CO_2 as a renewable carbon feedstock for clean fuel production.^[87] It is worth mentioning that this route for CO_2 reduction and fixation is effectively carried out in anaerobic bacteria by a nickel-containing enzyme carbon monoxide deshydrogenase (CODH)^[88] Remarkably, the active center of CODH bears a bimetallic Ni/Fe cluster where CO_2 is initially trapped as a bimetallic $\mu\text{-CO}_2$ complex (Figure 3).^[89] During the last decade, intensive efforts have been devoted to explore molecular catalysts for efficient electrocatalytic reduction of CO_2 based on Ni and Pd complexes with polydentate ligands.^[90]

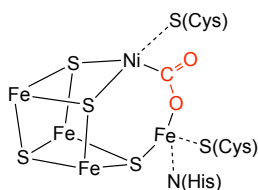
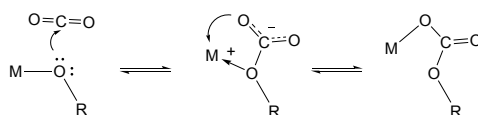


Figure 3. CO_2 binding to the active center of the carbon monoxide deshydrogenase (CODH).

The insertion of CO₂ into M-C and M-heteroatom bonds has also been the subject of much research.^[91] Specifically, CO₂ insertion into M-O bonds is relevant to the direct synthesis of organic carbonates and polycarbonates from CO₂,^[74,92] and is also of great biological significance, for example in the enzyme carbonic anhydrase.^[93] Early work on the carboxylation reactions of 18-e carbonylmetal alkoxides of the groups 6 and 7 (e. g. [W(CO)₅OPh]⁻ or *fac*-[Re(CO)₃(BIPY)(OR)]) showed that CO₂ insertion is faster than carbonyl dissociation. Hence, it does not require the generation of a coordination vacancy, in contrast with the migratory insertion route preferred by CO. The commonly accepted view of the mechanism CO₂ receives the attack of the lone electron pair of the metal-bonded oxygen. The rearrangement of the initial product to the final insertion product involves a shift metal fragment to one of the terminal oxygen atoms, as shown in Scheme 21.

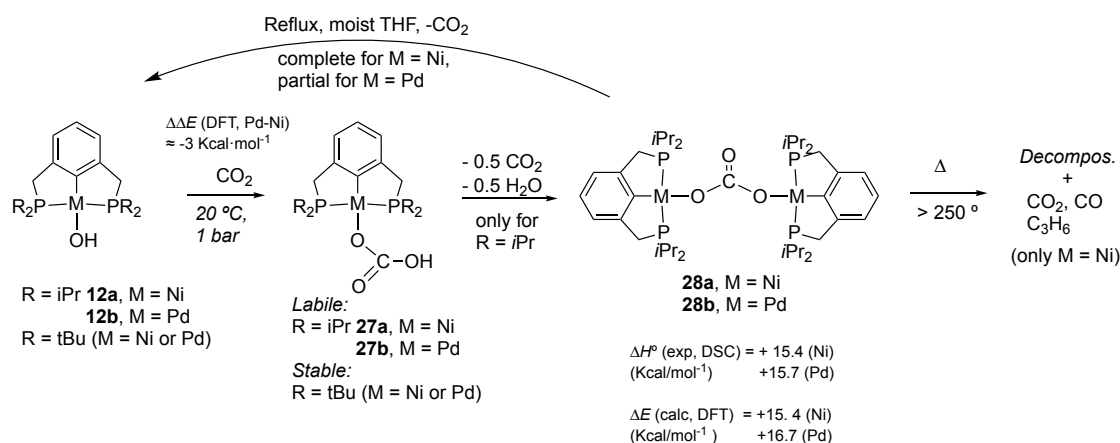


Scheme 21. Non-migratory CO₂ insertion mechanism by direct attack on an alkoxide ligand

The use of pincer ligands has proved especially useful for the study of reactions of CO₂ in isolated M-O bonds. Much of the work reported in the literature has concentrated in the reactivity of hydroxide complexes.^[84,94-97] The nucleophilic attack of the hydroxide ligand on CO₂ involves a very low energy barrier, hence it overrides the migratory insertion pathway even in coordinatively unsaturated 16-e systems, like square-planar *d*⁸ systems.^[94] This is reflected in the facile and almost instantaneous carboxylation of many types of monomeric M-O bonds, whereas CO₂ insertion into comparable M-C bonds is usually more difficult.^[91a] Holm has reported stopped-flow kinetic data on the CO₂ insertion in anionic nickel hydroxides with 2,6-pyridinebiscarboxamidato ligands, showing that the rate of the extremely fast insertion reactions is controlled mainly by steric effects.^[94] The prime insertion product of these reactions are bicarbonate complexes.

Scheme 22 summarizes the behavior of ⁱPrPCP and ^tBuPCP M(II) hydroxides with CO₂. As observed in the related CO insertions, the steric bulk of the latter prevents the formation of binuclear derivatives, therefore the reaction of the hydroxides [(^tBuPCP)M-OH] (M = Ni^[95] or Pd^[84]) with CO₂ gives rise to stable bicarbonate products. However, in our study of the reactions of the ⁱPrPCP we found that, even though the initial outcome of the reaction gives are the corresponding bicarbonates **27a** and **27b**, these are rather unstable, readily undergoing partial decarboxylation and condensation to afford the binuclear carbonates **28a** and **28b**.^[96] The process is so facile that the loss of CO₂ occurs when their solutions are simply concentrated under vacuum. Full decarboxylation back to the hydroxides was observed when the carbonates were refluxed in wet THF. The reaction can be accomplished quantitatively for M = Ni, but in the

case of Pd is incomplete. A partial decarboxylation reaction from bicarbonate to carbonate was observed for a similar hydroxide with M = Pd and the hybrid pincer ligand ^tBuPCO, that contains CH₂P(^tBu)₂ and CH₂OMe donor fragments.^[97]



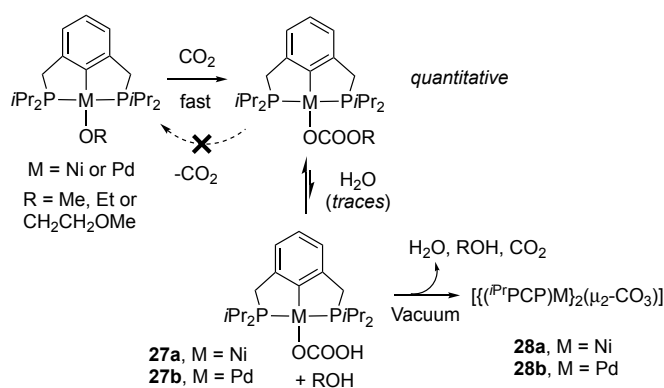
Scheme 22. Carboxylation of Ni and Pd hydroxide complexes with PCP pincer scaffolds.

The isolation of the unstable bicarbonate complexes **27** allowed their structural characterization and enabled us to study their decomposition in the solid state by DSC and TGA coupled with mass spectrometry. Both compounds show similar thermal behaviors, the simultaneous CO₂ and H₂O losses ensuing at temperatures slightly above the room temperature. The curves show endotherms with maxima at ca. 50 °C, corresponding to $\Delta H^\circ \approx +15 \text{ Kcal/mol}$. As in the decomposition of inorganic carbonates, CO₂ loss at higher temperatures afford oxo species and, for M = Ni (but not for Pd), a second endotherm was observed at 210° C. However, the mass spectra of the evolved gases showed that CO₂ is accompanied of significant amounts of CO and hydrocarbons, signaling the collapse of the pincer unit.

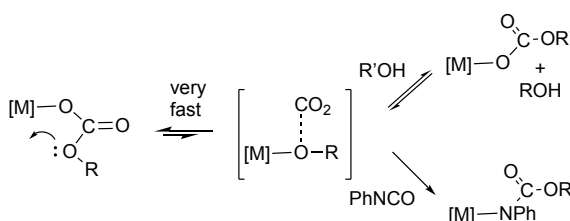
The spontaneous conversion of bicarbonates **27** into carbonates **28** is a consequence of the reversibility of CO₂ insertion into the Ni-O and Pd-O bonds. Furthermore, as mentioned above, hydroxides **12** can be regenerated from the carbonates **27** and water, with some more difficulty for Pd than for Ni. DFT calculations showed that CO₂ insertion into the M-OH bonds is ca. 3 Kcal/mol more exothermic for Pd than for Ni.^{95,96} DFT calculations for full geometries of the Ni and Pd bicarbonates **27** and binuclear carbonates **28** afforded reaction energies of 15.4 and 16.7 Kcal·mol⁻¹ for M = Ni and Pd, respectively, very close to the experimental ΔH° values from the DSC experiments.⁹⁶ These results confirm that that CO₂ insertion into M-OR bonds is somewhat more thermodynamically more favorable for Pd than for Ni.

The reactions of CO₂ with Ni and Pd alkoxides has received less attention, in part due to the difficulty for isolating pure samples the alkoxide complexes. Years ago, we reported that the nickel complex [Ni(O^tBu)(Me)(DiPPE)] reacts rapidly with CO₂, PhNCO or PhNCS, but insertion

products were only obtained in the two latter cases. In contrast, the analogous chemistry with the related amide $[\text{Ni}(\text{NC}_4\text{H}_8)(\text{Me})(\text{DiPPE})]$ led to the expected insertion products with all three reagents.^[53b] The availability of Ni and Pd pincer alkoxides $[(^i\text{PrPCP})\text{M}-\text{OR}]$ furnished an excellent opportunity to explore the reactivity of these compounds with CO_2 .^[98] Bubbling CO_2 in solutions of the alkoxides in C_6D_6 immediately causes quantitative conversion to the corresponding alkylcarbonate products $[(^i\text{PrPCP})\text{M}-\text{OCOR}]$. However, attempts to isolate the products by solvent evaporation led to contamination with variable amounts of the carbonates **28** (Scheme 23). The reason is the reversible exchange of the alkylcarbonate functionality with traces of water, to afford the corresponding bicarbonates. Upon evaporation, volatile components in the mixture (CO_2 and alcohol) are lost, causing the irreversible formation of the Ni or Pd carbonates. The process can be reverted, since both **28a** and **28b** react readily with alcohols. However, the thermodynamic balance for the insertion of CO_2 into the $\text{M}-\text{OR}$ bond is so favorable that the alkoxides cannot be regenerated from the alkylcarbonates by CO_2 removal under vacuum. Therefore, the ease of this hydrolytic decarboxylation is due to the kinetic lability of the $\text{M}-\text{OCOR}$ linkage, and is driven by the removal of volatiles under vacuum. In addition, the inserted CO_2 molecule is readily exchanged with isotopically labelled $^{13}\text{CO}_2$ or other unsaturated molecules, e. g. phenyl isocyanate, to yield a carbamate derivative (Scheme 24). Darensbourg has reported a similar reaction of the manganese methoxycarbonyl $[\text{Mn}(\text{OCOOMe})(\text{CO})_3(\text{dppe})]$ with SCO to afford the $[\text{Mn}(\text{SCOOME})(\text{CO})_3(\text{dppe})]$.^[99]

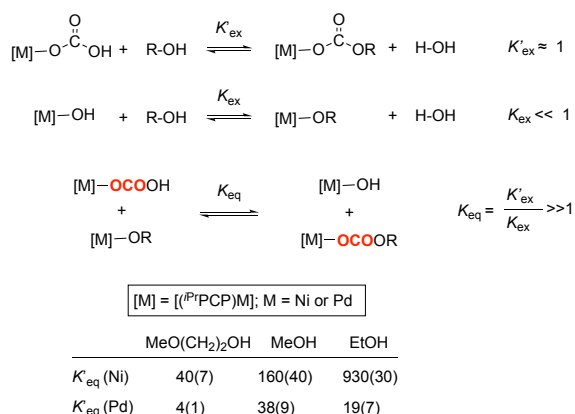


Scheme 23. Carboxylation and reversible hydrolysis of $^i\text{PrPCP}$ -based alkoxides of Ni and Pd.



Scheme 24. Kinetic lability of alkylcarbonate complexes

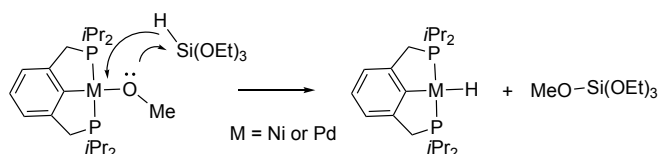
The lability of the alkoxycarbonates seems to be characteristic of the ⁱPrPCP systems.^[100] This feature prompted us to probe the relative stability of the bicarbonate and alkylcarbonate complexes, measuring the equilibrium constants for the reaction of the bicarbonate complexes with different alcohols, K'_{ex} (Scheme 25). Not surprisingly, the K'_{ex} values are close to unit, because the far-removed R group has little effect on the thermodynamic stability of the complex. Notice that, as shown in Scheme 25, the K'_{ex} constants can be composed with those of the above-discussed hydroxide-alcohol exchange (K_{ex} , see also Scheme 17) to compute the constants K_{eq} . These constants describe a hypothetical CO₂ redistribution equilibria involving bicarbonates and alkylcarbonates. K_{eq} measures the relative tendency of CO₂ to insert into a given M-OR bond, with regard to the same process in the M-OH bond. These are always significantly higher than unit, indicating that CO₂ insertion is invariably more favorable for the M-OR bond than the M-OH. This reflects the fact that the stronger bond is usually the least reactive. The differences are more acute for the Ni than the Pd compounds, as expected for the stronger electrostatic effects associated to the shorter Ni-O bonds. Consistent with these data, we observed that alkylcarbonate species [(ⁱPrPCP)M-OCOOR] are formed preferentially over the bicarbonates. The preference is so high that, in the presence of alcohol, the hydroxides react with CO₂ to give directly the alkylcarbonates, rather than bicarbonates. This circumstance is fortunate for the design of processes aimed at the incorporation of CO₂ in carbonate-type products.^[98]



Scheme 25. Use of reversible water-alcohol exchange to probe the thermodynamics of CO₂ into different M-OR bonds.

As mentioned before, the reactions of alkoxides with CO and CO₂ are archetypical examples of the main mechanisms of insertion, namely migratory route and direct attack on a coordinated ligand. Because nucleophilicity is the dominant feature of hydroxides, alkoxides and other compounds with reactive M-O bonds, they tend to react more frequently through the second pathway. Therefore, small molecules with marked electrophilic character, like heterocumulenes of various sort (e. g. CS₂, RNCO or RNCS),^[53b,79] aldehydes,^[20a] as well as acid oxides like SO₂^[101] do insert readily into M-O bonds, whereas migratory insertions, so prevailing

in the reactivity of M-C bonds are much less common. Only substrates with exceptional binding capacity like CO can override the natural tendency of the alkoxide to fill up any coordination vacancy by electron pair donation. However, the adequate selection of ancillary ligands may overcome this situation, and some fascinating examples of migratory insertions of olefins into M-N and M-O bonds have been reported.^[102] On the other hand, the nucleophilic reactivity of covalently bond M-O ligands is not limited to insertion reactions. Electrophilic M-OR bond cleavage is a very common reaction for metal alkoxides. In addition to cleavage by protic acids (already discussed as a acid-base reaction), these include a number of potentially useful reactions with a variety of electrophiles. Alkylation with alkyl halides and sulfonates has received relatively little attention. We recently showed that nickel and palladium alkylcarbonates [(*i*Pr₂PCP)MOCOOR] do react with methyl iodide or methyl triflate to afford the corresponding carbonates, MeOCOOR, and the corresponding iodide or triflate complex as byproducts.^[98] The reaction is efficient for Pd and sluggish fo Ni, which affords lower yields of the organic carbonate, illustrating the higher nucleophilicity of the former. A similar reaction with Zn methylcarbonates was reported by Vahrenkamp to afford mainly dimethylether, after CO₂ extrusion.^[103] In addition, Ni and Pd alkoxides do react with silanes to afford hydrides, a reaction that very likely involve nucleophilic attack of the alkoxide on silicon. A well-characterized example of this type of reaction, used as a preparative method for the syntheses of hydrides,^[54] is shown in Scheme 26. This process constitutes an important step in catalytic hydrosilylation of carbonyl compounds.^[48a,104] Zargarian has explored similar reactions of nickel siloxide complexes with silanes. These may entail not only the metal-siloxide linkage, but can also MO-SiR₃ bonds.^[105] Nucleophilic attack of reactive palladium or nickel hydroxide species on organoboron reagents is involved in the key transmetalation step that takes place in the Suzuki-Miyaura reaction.^[13,14]



Scheme 26. M-OMe bond cleavage by silanes to yield hydride complex and siloxide.

Summary and Outlook

Over the past two decades, the chemistry of Ni and Pd hydroxide and alkoxide complexes has experienced a considerable development. Such advances have been possible by the use of suitable polydentate ligands, in special tridentate pincer scaffolds that stabilize the alkoxide fragment and prevent the aggregation of the alkoxide unit as polynuclear or insoluble species. This allows the confinement of reactive metal-oxygen bonds in molecular pockets that can be

tailored to harness their reactivity, in a way somehow reminiscent of enzymes. However, an important advantage of small rigid ligands is their relative simplicity, accessible to detailed mechanistic and theoretical investigation. Research in this direction has highlighted the similarities and differences between discrete alkoxides and alkyls. Perhaps one of the most salient developments is the elucidation of the roles of thermodynamic and kinetic control on the chemical reactivity of alkoxides. Contrary to some early ideas that invoked HSAB theory concepts or repulsive nonbonding interactions between *p-d* filled orbitals, neither the available experimental evidence and computational analysis support the concept that late transition metal-oxygen bonds are weak.

Much of the high reactivity that in practice characterizes late transition metal alkoxides has a kinetic origin. The presence of reactive lone electron pairs localized directly on the metal-bonded oxygen atom provide a highly reactive basic/nucleophile site that can be readily attacked by acids and electrophiles. An example is the extremely facile exchange with weak acids like water, which is the cause of the high hydrolytic sensitivity of Ni and Pd alkoxides. DFT calculations have also demonstrated that these lone electron pairs assist migratory insertion of CO, and promote the insertion of CO₂ by directly donating into the empty π^* orbital of the electrophilic molecule before it interacts with the metal center.

It is remarkable that quantitative measurements show that Ni complexes are thermodynamically more prone to hydrolysis than their Pd congeners, despite the nucleophilicity and lower thermal stability of the latter. This difference is a consequence of the highly polar nature of the M-O bonds. The ionic stabilization forces are stronger for Ni but, at the same time, this implies a larger bias in favor of hydroxides over alkoxides. Such polarity effects also control the selectivity other reactions under thermodynamic control, like CO₂ insertion, appreciably more favorable for the M-OR than for the M-OH bond. An interesting consequence of this is that, whereas the M-OR complexes are very prone to hydrolysis, the trend is reverted in the presence of CO₂ and alkylcarbonates M-OCOOR become preferred over bicarbonates M-OCOOH.

Despite the progress in the understanding of the reactivity of late transition metal alkoxides and related complexes, there is much to be said still on the reactivity of the organometallic-like reactivity of metal-element bond. Thus, it is not clear yet to which extent the active role of the heteroatom lone electron pairs could be enhanced by their repulsive, nonbonding interactions with the filled *d* orbitals in the metal. Although such interactions play a quantitatively minor role on the stability of the M-O bonds, they certainly exist and manifest in spectroscopic and structural effects. Destabilization of the oxygen lone pairs may have a role increasing their nucleophilicity. Furthermore, it is uncertain whether the lower M-O bond strength predicted by DFT calculations for Pd as compared to Ni, has to do only with the decreased contribution of

ionic bonding, or there is also a reduction in the covalent contribution, as predicted by the HSAB theory.

As mentioned in the Introduction, the combination of "organometallic-like" reactivity with exceptional basicity and nucleophilicity makes the chemistry of well-defined, discrete alkoxides of the late transition metals a fascinating subject. To this it should be added that the alcohols, phenols and their derivatives compounds are one of the most abundant substances in natural resources and their transformation is one of the keys in Organic Synthesis. There are many applications of palladium catalysts for the transformation of functional groups carbon-heteroatom coupling (e. g., Buchwald-Hartwig amination, and its etherification counterpart) or alcohol oxidation that rely on the properties of Pd-heteroatom bonds. Extending some of with applications to Ni catalysts, or other first-row, non-precious metals will augment the versatility of the available reactions and contribute to reduce the costs associated with the use of scarce and essentially non-renewable metals.

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