Inorganic Chemistry

Communication

Rhenium(V) Complexes with Pentadentate P,N,O Ligands
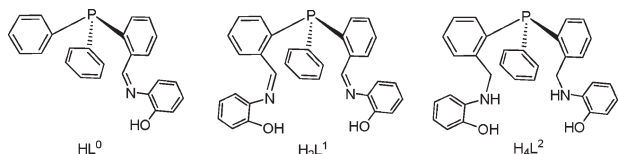
Ali Barandov and Ulrich Abram*

Freie Universität Berlin, Institute of Chemistry and Biochemistry, Fabeckstr. 34-36, D-14195 Berlin, Germany

Novel rhenium(V) complexes were isolated from reactions of [NBu$_4$][ReOCl$_4$] with the potentially pentadentate Schiff base PhP{C$_6$H$_4$-2-(HC=N(C$_6$H$_4$-2-OH))}$_2$, H$_2$L^1, and the corresponding amine PhP{C$_6$H$_4$-2-(CH$_2$−NH(C$_6$H$_4$-2-OH))}$_2$, H$_4$L^2. While the Schiff base undergoes partial hydrolytic decomposition and a redox reaction, the amine remains intact and acts as a pentadentate ligand, which encapsulates the metal atom of the {Re^{V}O}$^{3+}$ core or stabilizes a {Re^{V}Cl}$^{4+}$ center by the formation of an imido-type ligand system.

Despite the fact that pentadentate ligand systems would be perfectly suitable for the stabilization of {Re^{V}O}$^{3+}$, {Re^{V}NPh]$^{3+}$, or {Re^{V}N}$^{2+}$ cores, which are under discussion for applications in nuclear-medical therapy with the β^--emitting isotopes ^{186}Re and ^{188}Re,[1] there are only a few examples of structurally well-characterized complexes.[2] Decomposition or incomplete coordination of potentially pentadentate ligands was observed instead in a number of additional examples.[3]

The ready availability of formylphosphines of the composition Ph$_{3-n}$P(2-C$_6$H$_4$CHO)$_n$ (n = 1−3)[4] gives access to Schiff bases, which may contain additional donor atoms such as from hydroxylic, thiol, or carboxylic groups and their derived amines. Recently, we reported about reactions of rhenium complexes with Ph$_2$P(C$_6$H$_4$-2-HC=N(C$_6$H$_4$-2-OH) (HL^0) and its amine derivative.[5]

Here, we extend this work to the potentially pentadentate ligand systems H$_2$L^1 and H$_4$L^2. H$_2$L^1 was synthesized through a standard imine condensation between bis(2-formylphenyl)phenylphosphine and 2 equiv of 2-aminophenol.[6] The product was isolated as a yellow solid in a high yield. The ^{31}P-{^{1}H} spectrum of the product shows a single resonance at −18 ppm. A doublet at 9.1 ppm (J_{PH} = 4.9 H) in the ^{1}H NMR spectrum of H$_2$L^1 suggests the presence of the HC=N unit.

H$_2$L^1 reacts with an excess of NaBH$_4$ in boiling ethanol under reduction of the imine function and formation of the related secondary amine H$_4$L^2.[6] The ^{31}P-{^{1}H} NMR spectrum presents a single resonance at −27.4 ppm. The 9 ppm low-field shift with respect to H$_2$L^1 is consistent with the loss
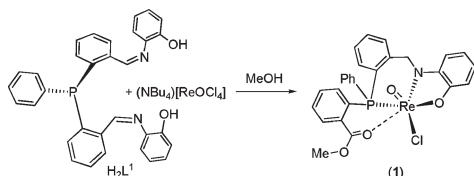
(3) (a) Chen, X.; Femia, F. J.; Babich, J. W.; Zubieta, J. *Inorg. Chim. Acta* **2000**, *310*, 237. (b) Banbery, H. J.; McQuillan, F.; Hamor, T. A.; Jones, C. J.; McCleverty, J. A. *Polyhedron* **1989**, *8*, 559.

(4) Del Zotto, A.; Baratta, W.; Ballico, M.; Herdtweck, E.; Rigo, P. *Organometallics* **2007**, *26*, 5636.

(5) Barandov, A.; Abram, U. *Polyhedron* **2009**, *28*, 1155.

(6) Synthesis of H$_2$L^1. Bis(2-formylphenyl)phenylphosphine (1 g, 3.1 mmol) and 2-aminophenol (0.7 g, 6.2 mmol) were suspended in 10 mL of ethanol and heated under reflux for 1.5 h. A yellow solid precipitated upon cooling. The product was filtered off and washed with cold ethanol. Yield: 1.3 g (82%). For analytical and spectroscopic data, see the Supporting Information. Synthesis of H$_4$L^2. H$_2$L^1 (1.5 g, 3 mmol) and NaBH$_4$ (1.7 g, 48 mmol) were suspended in 20 mL of EtOH and heated. The color of the reaction mixture turned to colorless within 10 min. Subsequently, the solvent was evaporated to dryness under a vacuum and the product extracted by 50 mL of a THF/toluene mixture. The organic phase was washed with water and dried over MgSO$_4$. H$_4$L^2 was isolated as a colorless solid after removal of all volatiles under a vacuum. Yield: 1.3 g (86%). For analytical and spectroscopic data, see the Supporting Information.

(7) Synthesis of [ReOCl(L^{1a})] (1): Solid H$_2$L^1 (50 mg, 0.1 mmol) was added to a solution of [NBu$_4$][ReOCl$_4$] (58 mg, 0.1 mmol) in 10 mL of MeOH, which was not dried previously. The mixture was stirred at room temperature for 30 min. During this time, a clear brown solution was formed, from which a brown solid precipitated. The product was filtered off and washed with cold methanol. Yield: 28 mg (41%). For analytical and spectroscopic data, see the Supporting Information. Synthesis of [ReCl(L^2)] (2): H$_4$L^2 (50 mg, 0.1 mmol) was added to a solution of [NBu$_4$][ReOCl$_4$] (58 mg, 0.1 mmol) in 5 mL of MeOH. The color of the solution turned immediately to cherry red, and after the reaction solution was stirred at 50 °C for 2 h, a microcrystalline solid was obtained. The solid was filtered off and washed with MeOH. The product was recrystallized from a CH$_2$Cl$_2$/MeOH mixture. Yield: 50 mg (68%). For analytical and spectroscopic data, see the Supporting Information. Synthesis of [ReO(HL^2)] (3): Solid H$_4$L^2 (50 mg, 0.1 mmol) was added to a solution of [NBu$_4$][ReOCl$_4$] (58 mg, 0.1 mmol) in 10 mL of MeOH and stirred for 30 min. Thereafter, NEt$_3$ (0.3 mL) was added, and the reaction mixture was stirred at ambient temperature for another 1 h. The product, which precipitated directly from the reaction mixture, was filtered off and washed with MeOH. Recrystallization from THF gave red crystals of [ReO(HL^2)]. Yield: 62 mg (81%). For analytical and spectroscopic data, see the Supporting Information.

*To whom correspondence should be addressed. E-mail: abram@chemie.fu-berlin.de.

(1) (a) Deutsch, E.; Libson, K.; Vanderheyden, J.-L.; Ketring, A.; Maxon, H. R. *Nucl. Med. Biol.* **1986**, *13*, 465. (b) Jurisson, S.; Berning, D.; Jia, W.; Ma, D. *Chem. Rev.* **1993**, *93*, 1137. (c) Abram, U.; Alberto, R. *J. Braz. Chem. Soc.* **2006**, *17*, 1486.

(2) (a) Tisato, F.; Refosco, F.; Mazzi, U.; Bandoli, G.; Nicolini, M. *Inorg. Chim. Acta* **1991**, *189*, 97. (b) Kramer, A.; Alberto, R.; Egli, A.; Novak-Hofer, I.; Hegetschweiler, K.; Abram, U.; Bernhardt, P. V.; Schubiger, P. A. *Bioconjugate Chem.* **1998**, *9*, 691. (c) Luo, H.; Liu, S.; Rettig, S. J.; Orvig, C. *Can. J. Chem.* **1995**, *73*, 2272. (d) Abrahams, A.; Gerber, T. I. A.; Luzipo, D. R; Mayer, P. S. *J. Coord. Chem.* **2007**, *60*, 2213.

Scheme 1. Synthesis of [ReOCl(L^{1a})]

of the electron-withdrawing imine groups and the presence of the electron-donating methylene components. A less-resolved doublet at 4.4 ppm and a broad signal at 5.4 ppm are associated with the methylene and amine protons. The stretching vibrations of the NH and OH components were detected as broad bands at 3514 and 3425 cm^{-1} in the IR spectrum of H$_4$L^2.

The reaction of H$_2$L^1 with [NBu$_4$][ReOCl$_4$] gives the unexpected product [ReOCl(L^{1a})] (**1**), where H$_2$L^{1a} is PhP-(C$_6$H$_4$-2-COOMe){C$_6$H$_4$-2-(CH$_2$−NH(C$_6$H$_4$-2-OH))}.[7] One of the imine groups of the initially used Schiff base ligand undergoes successive hydrolysis/solvolysis reactions, which are accompanied by the oxidation of the carbon atom and the formation of an ester. The two released electrons are consumed in the reduction of the second imine group to the related amine (Scheme 1). Decomposition of Schiff bases during reactions with rhenium complexes is not without precedent, and several complexes with coordinated fragments, such as amine, arylimido, alcoholato, or hemiacetals, are described.[2c,3a,8,9] Oxidative hydrolysis of an imine group was observed for Re(V) complexes with diazabutadiens, and Re(IV) and Re(III) products were isolated as products.[10] Although the mechanism of the present redox process is not yet fully clear, it is most probable that the reaction is metal-induced or at least metal-mediated. This is strongly suggested by the coordinative bonding of the central phosphorus atom (no formation of phosphine oxide or rhenium complexes with the metal in other oxidation states was detected during the entire reaction) and the fact that no evidence for the formation of H$_2$L^{1a} was found during a treatment of H$_2$L^1 with methanol. Thus, an intramolecular redox process is probable, despite the fact that the yield of the isolated compound **1** was less than 50%.

The ^{31}P NMR spectrum of **1** shows a single resonance at 21.9 ppm associated with the coordinated phosphine. The ^{1}H NMR spectrum confirms the presence of the ester function by a singlet at 3.5 ppm. The electrospray ionization (time of flight) mass spectrum of **1** supports the molecular structure by a base peak at 678.1 amu associated with a [M + H]$^+$ species. The coordination environment of the rhenium atom is a distorted octahedron with only weak Re−O2 interactions (Figure 1).[11] The bond lengths N1−C7 of 1.43(1) Å and C11−N1 of 1.43(1) Å are in the range of the single bonds, which is consistent with the reduction of the imine group to the related amine function. The O2−C27 bond of 1.22(1) Å and the O2−C27−O3 angle of 121.9(8)° confirm the presence of the ester function.
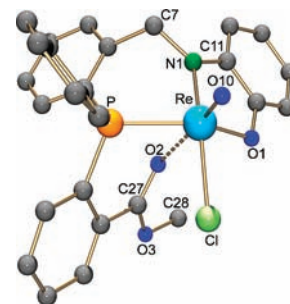
Figure 1. Molecular structure of **1**.[12] Hydrogen atoms are omitted for clarity. Selected bond lengths: Re−O10, 1.675(7); Re−P, 2.394(2); Re−N1, 1.967(8); Re−O1, 1.973(8); Re−Cl, 2.435(2); Re−O2, 2.414(7); N1−C11, 1.43(1); N1−C7, 1.44(1); C27−O2, 1.22(1); C27−O3, 1.31(1) Å.

Scheme 2. Synthesis of [ReCl(L^2)] (**2**) and [ReO(HL^2)] (**3**)
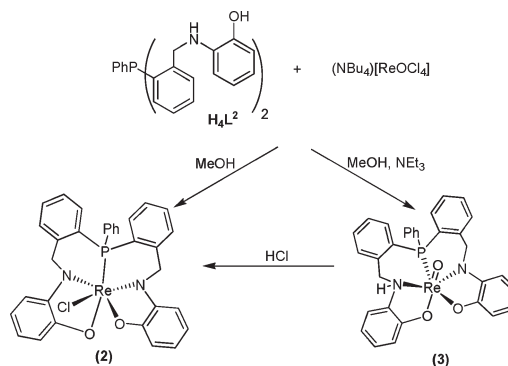
Undesired and uncontrollable reactions in the novel multidentate ligand system during reactions with rhenium precursors can be avoided, when the Schiff base is reduced to the corresponding secondary amine. The resulting potentially pentadentate aminophosphine H$_4$L^2 reacts with [NBu$_4$]-[ReOCl$_4$] under the formation of different products depending on the experimental conditions. Reactions in neat methanol give a product of the composition [ReCl(L^2)] (**2**) in good yields, while similar reactions in the presence of the supporting base NEt$_3$ yield the oxorhenium(V) complex [ReO(HL^2)] (**3**) (Scheme 2).

[ReCl(L^2)] (**2**) belongs to some rare examples of rhenium(V) complexes, which do not contain one of the common ReO^{3+}, ReN^{2+}, or Re(NPh)$^{2+}$ cores. Other representatives are [ReCl$_5$], [Re(HNC$_6$H$_4$S)$_3$]$^-$, and the mixed-ligand complexes [ReCl(PPh$_3$)(NHC$_6$H$_4$S)$_2$] and [ReCl(PPh$_3$)(L)$_2$] (L = 3-nitro-1,2-diamidobenzene).[13]

Both compounds **2** and **3** are diamagnetic. Their ^{31}P NMR spectra show single resonances of the coordinated phosphines at +11.1 ppm (**2**) and −4.8 ppm (**3**). The absence of the NH and OH stretching vibrations in the range of 3100−3500 cm^{-1} in the IR spectrum of **2** is consistent with the deprotonation of both amine groups of the phosphine ligand, while a medium band at 3178 cm^{-1} in the IR spectrum of **3** can be assigned to a NH stretch. The ^{1}H NMR spectra of **2** and **3** support the complete or partial deprotonation

(8) Abram, U. Rhenium. In *Comprehensive Coordination Chemistry II*; McCleverty, J. A., Mayer, T. J., Eds.; Elsevier: Amsterdam, The Netherlands, 2003; Vol. *5*, p 271.

(9) Barandov, A. Ph.D. Thesis, Freie Universität, Berlin, 2009.

(10) Das, S.; Chakraborty, I.; Chakravorty, A. *Inorg. Chem.* **2003**, *42*, 6545.

(11) For details about the structure determinations and bond lengths and angles, see the Supporting Information.

(12) Farrugia, L. J. *J. Appl. Crystallogr.* **1997**, *30*, 565.

(13) (a) Cotton, F. A.; Robinson, W. R.; Walton, R. A. *Inorg. Chem.* **1967**, *6*, 223. (b) Mucker, K.; Smith, G. S.; Johnson, Q. *Acta Crystallogr.* **1968**, *B24*, 874. (c) Gardner, J. K.; Pariyadath, N.; Corbin, J. L.; Stiefel, E. I. *Inorg. Chem.* **1978**, *17*, 897. (d) Bandoli, G.; Dolmella, A.; Gerber, T. I. A.; Perils, J.; du Preez, J. G. H. *Inorg. Chim. Acta* **2000**, *303*, 24.
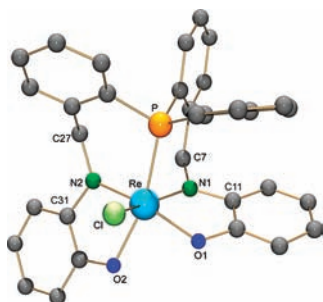
Figure 2. Structure of complex **2**.[12] Hydrogen atoms are omitted for clarity. Selected bond lengths: Re−Cl, 2.379(3); Re−O1, 2.018(9); Re−O2, 2.048(8); Re−N1, 1.961(9); Re−N2, 1.935(9); Re−P, 2.354(3); N1−C11, 1.38(1); N1−C7, 1.47(2); N2−C31, 1.42(2); N2−C27, 1.49(2) Å.
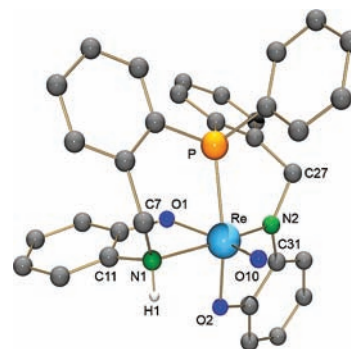
situation of the pentadentate ligand in both complexes, as given in Scheme 2. The NH resonance is detected at 8.9 ppm in the ^{1}H NMR spectrum of **3**, while the spectrum of **2** presents no signal in the range of 8.1−10.0 ppm.

X-ray diffraction confirms the structure of [ReCl(L^2)] (**2**) as a distorted octahedral rhenium complex with a 4-fold deprotonated, pentadentate phosphine ligand (Figure 2).[11] A chloro ligand occupies the sixth position. The bond lengths between N1−C11 of 1.38(1) Å and Re−N1 of 1.96(1) Å are shorter than typical single bonds. This implies a partially double-bond characteristic resulting from the conjugation of the lone pair of N1 with the π electrons of the adjacent phenyl ring [C11 to C16] and unoccupied orbitals of the metal. The presence of a partial double-bond character is confirmed by the planar environment of N1 (angles: C11−N1−C7, 117(1)°; C11−N1−Re, 119.4(8)°; Re−N1−C7, 122.1(7)) The second nitrogen atom N(2) shows a similar planar orientation, despite the fact that the corresponding C−N bond lengths are in the range of single bonds of rhenium complexes with secondary amines.[14] The Re−N(2) bond length of 1.93(1) Å, however, has marked double-bond character.

The double-bond character of the Re−N bonds in **2** explains the diamagnetism of the formed d^2 amido/imido complex by a similar bonding situation like in rhenium(V) complexes with oxo, nitrido, or phenylimido cores.[8] The formation of imido species from oxo compounds under acidic conditions corresponds to the general procedure that is also applied for the synthesis of phenylimides from oxo complexes.[8] Protonation of the oxo core is most likely the first step of such reactions. This is avoided when a supporting base such as NEt$_3$ is added. Consequently, the oxo core is retained under such conditions, and compound **3** is formed (Figure 3). The essential role of the presence of protons in such reactions


Figure 3. Structure of complex **3**.[12] Hydrogen atoms bonded to carbon atoms are omitted for clarity. Selected bond lengths: Re−O10, 1.687(6); Re−O1, 2.035(6); Re−O2, 2.016(7); Re−N1, 2.035(6); Re−N2, 1.943(8); Re−P, 2.400(3); N1−C11, 1.45(1); N1−C7, 1.46(2); N2−C31, 1.40(1); N2−C27, 1.49(1) Å.

is underlined by the fact that the oxo complex **3** is readily converted into **2** by the addition of HCl to a THF solution of the compound.[15] Thus, compound **3** can be regarded as an intermediate of the formation of **2** from [ReOCl$_4$]$^-$. However, no evidence was found for the formation of dioxo or μ-oxo dimers during our studies with the pentadentate ligands.

The chelating phosphine ligand shows a pentadentate coordination also in the oxo complex **3**. One of its nitrogen atoms, however, remains protonated, which goes along with a slightly longer Re−N1 bond compared to the Re−N2 bond and the bonding situation in **2**.

The pentadentate phosphine H$_4$L^2 is the first representative of a novel, versatile class of ligands, which are well-suited for the formation of stable complexes with rhenium(V) and also technetium(V) centers. The stability of the resulting amido/imido complex justifies the use of this new class of compounds in further experiments, particularly such as the synthesis of bioconjugates with ^{186,188}Re or ^{99m}Tc. For the synthesis of radioactive bioconjugates with peptides or proteins using this new class of compounds, the attachment of an anchor group is required. The new ligand systems possess remarkable synthetic potential in this field. Corresponding experiments with bioconjugatable derivatives such as H$_2$L^3 are being performed in our laboratory, and such with H$_4$L^4 are planned for the near future.
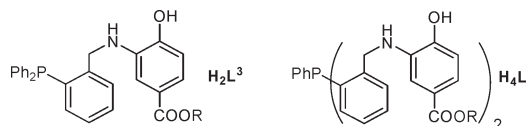
Supporting Information Available: Experimental procedure descriptions, additional figures and tables, and a crystallographic information file. This material is available free of charge via the Internet at http://pubs.acs.org.

(14) Basak, S.; Rajak, K. K. *Inorg. Chem.* **2008**, *47*, 8813.
(15) Compound **3** (0.1 mmol) was dissolved in 3 mL of THF, and 100 μL of aqueous HCl (36 w%) was added. An immediate color change from brown to cherry red was observed, and the ^{31}P NMR spectrum of the resulting solution confirms the complete conversion from **3** into **2** within 5 min. Expectedly, the reverse reaction, the conversion of the amido/imido complex **2** into the oxo compound **3** by the addition of base Et$_3$N or NaOH/MeOH), is not observed.