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Metalloraldrad Reactivity of Ru\(^{1}\) and Ru\(^{0}\) Stabilized by an Indole-Based Tripodal Tetraphosphine Ligand

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Abstract: The tripodal, tetradeinate tris(1-(diphenylphosphanyl)-3-methyl-1H-indol-2-yl)phosphane PP\(_3\)-ligand 1 stabilizes Ru in the Ru\(^{2}\), Ru\(^{3}\), and Ru\(^{0}\) oxidation states. The octahedral \([\text{PP}_3]\text{Ru}^2(\text{Cl})\) (2), distorted trigonal bipyramidal \([\text{PP}_3]\text{Ru}^3(\text{Cl})\) (3), and trigonal bipyramidal \([\text{PP}_3]\text{Ru}^0(\text{N}\_3)\) (4) complexes were isolated and characterized by single-crystal X-ray diffraction, NMR, EPR, IR, and ESI-MS. Both open-shell metalloradical Ru\(^{2}\) complex 3 and the closed-shell Ru\(^{0}\) complex 4 undergo facile (net) abstraction of a Cl atom from dichloromethane, resulting in formation of the corresponding Ru\(^{2}\) and Ru\(^{0}\) complexes 2 and 3, respectively.

Metals of the 4d and 5d row of the periodic table, particularly late transition metals in low oxidation states, strongly prefer closed-shell 16 or 18 valence electron configurations. As a result, open-shell complexes of these metals are rare, and have a strong tendency to convert into closed-shell products.[1] Ru\(^{2}\) metalloradicals are particularly rare[a] and only two types of Ru\(^{2}\) complexes have been successfully isolated thus far. Peters and co-workers reported a five-coordinate 17-electron [Ru\(_2\)(SiP\(_3\))\(_3\)] complex supported by an anionic tripodal tetradeinate (SiP\(_3\))\(^{-}\) ligand (SiP\(_3\)\(^{-}\) = (2-Pr\(_2\)PC\(_6\)H\(_4\))\(_3\)Si). Besides Ru\(^{2}\), this platform also stabilizes complexes in oxidation states ranging from Ru\(^{2}\) to Ru\(^{0}\).[5] Interestingly, the Ru\(^{2}\) complex was shown to catalyze coupling of aryl azides to azoanemesis.[6] Recently, the group of Grützmauer reported the remarkable 4-coordinate 15-electron complex [Ru\(_2\)(tropPP\(_3\))\(_2\)]BF\(_4\) featuring two bidentate tropPP\(_3\) ligands (trop = 5H-dibenz[a,d]cyclohepten-5-yl)]. Besides Ru\(^{2}\), this ligand scaffold stabilizes ruthenium complexes in oxidation states ranging from Ru\(^{2}\) to Ru\(^{0}\).[3] No further reactivity with this complex has been reported to date.

Inspired by these intriguing examples, we wondered whether stable metalloradical Ru\(^{2}\) complexes could be accessed in a rigid tripodal PP\(_3\) ligand environment for subsequent reactivity evaluation. The above-mentioned Ru\(^{2}\) complexes feature either a strongly σ-donating anionic tripodal (SiP\(_3\))\(^{-}\) ligand or two neutral π-accepting bidentate (tropPP\(_3\)) ligands. Hence, we surmised that the use of a tripodal tetradeinate ligand featuring both σ-donor and π-accepting phosphorus groups could allow for isolation and reactivity studies of well-defined Ru\(^{2}\) metalloradicals. We turned our attention to the tripodal, tetradeinate tris(1-(diphenylphosphanyl)-3-methyl-1H-indol-2-yl)phosphane ligand (I)[4] (Figure 1), which we previously used to stabilize the metalloradical rhodium complex [Rh\(^{1}\)(1Cl)](PF\(_6\)).[8] We further wondered whether the corresponding ruthenium(0) complex could also be accessible and if these low-valent species would display interesting reactivity.

Figure 1. Ligand systems capable of stabilizing isolable Ru\(^{2}\) species.

First, we aimed at the synthesis of the Ru\(^{2}\) complex with ligand 1, as this species could allow entry to the desired low-valent ruthenium species by subsequent selective reduction. The desired complex [Ru(1)(Cl)] (2) was readily prepared by reacting stoichiometric amounts of 1 and [Ru(Cl)](C\(_6\)H\(_6\))\(_2\) in refluxing THF in good yield (Scheme 1).

The \(^{31}\)P NMR spectrum of complex 2 displays a triplet of doublets (\(\delta = 101.0\) ppm, \(J_{PP} = 26.4, 25.5\) Hz), an apparent triplet (\(\delta = 77.8\) ppm, \(J_{PP} - 26.5\) Hz), and a triplet of doublets (\(\delta = 48.5\) ppm, \(J_{PP} = 27.9, 26.9\) Hz) with the integral ratio 1:2:1. The presence of three different phosphorus NMR signals points to a geometry in which two equatorial amorphophosphine donors...
are equivalent ($d = 77.8$ ppm), whereas the third side-arm donor P3 ($d = 101.0$ ppm) experiences a different coordination environment. The pivotal, axial phosphine P4 is assigned to the signal at $d = 48.5$ ppm. RuII complexes with tripodal tetraphosphine ligands often display five-coordination with either square pyramidal or trigonal bipyramidal geometries around the metal center,

[8] however in case of complex 2, a nonca
drd geometry could not be excluded. Single crystals of 2, suitable for single crystal X-ray diffraction, were obtained by layering a dichloromethane solution with pentane. The molecular structure (Figure 2) reveals a distorted octahedral geometry, with $P1$–Ru1–$P2$ of 160.04(3)° (See the Supporting Information, Table S1) for the two mutually trans aminophosphines in the equatorial plane. The P donors oriented trans to the chlorido ligands have shorter Ru–P distances (Ru1–P3 (2.2671(9)/C138; Ru1–P4 (2.1932(9)/C138; Ru1–P1 (2.3727(9)/C138; Ru1–P2 (2.3189(9)/C138).

To explore the capability of 1 to stabilize low oxidation states of ruthenium, we attempted to determine the RuII/RuI and RuI/Ru0 reduction potentials of 2. The cyclic voltammogram of 2 in dichloromethane did not show any reduction wave within the solvent window ($E_{\text{red}} = -2.5$ vs. Fc/Fc+), and the poor solubility of 2 in THF, DMF, acetonitrile, or toluene prevented determination of the reduction potentials of 2 below $-2.5$ V. Thus, reduction of complex 2 to the desired complex [Ru(1)Cl] (3) requires a stronger reducing agent than the previously reported RuI complexes [1.24 V (RuII/RuI) and $-2.14$ V (Ru/I/Ru)] for the SiP3 system in THF; $+0.4$ V (RuII/RuI) and $-0.3$ V (Ru/I/Ru) for the tropPPh2 complex]. Therefore, we used KC8 to access the desired RuI and Ru0 species chemically (Scheme 2).

The addition of one molar equivalent of KC8 to a yellow suspension of 2 in THF resulted in a brown solution. The product formed proved to be NMR silent, suggestive of formation of a paramagnetic RuI species formed by one-electron reduction. X-band EPR spectroscopy confirmed the presence of the metallo
dradical species [Ru(1)Cl] (3). The EPR spectrum reveals a rhombic (albeit almost axial) g-tensor, characteristic of an $S = 1/2$ system (Figure 3). Hyperfine coupling interactions (HFIs) with two P atoms are resolved, in line with previous observations for tripodal tetradentate phosphine RuI complexes.[2c,e, 3]
These results are in agreement with a geometry that is distorted from a trigonal bipyramidal toward a (distorted) square pyramidal Ru′ coordination geometry. Preference for such a Jahn–Teller distorted trigonal bipyramidal geometry has also been observed for other d⁷ transition metal complexes.⁹

Simulation of the experimental EPR spectrum revealed the parameters shown in Table S2 (see also the captions of Figures 3 and 5). The geometry of 3 was optimized with DFT (Turbomole, BP86, def2-TZVP), and the EPR parameters were computed with Orca and ADF. The DFT-computed EPR parameters (Table S2) are in qualitative agreement with the experimental data. The computations reveal a mainly metal-centered spin density distribution, as evident from the singly occupied molecular orbital (SOMO) and spin density plots of 3 (Figure 4).

The SOMO of the metalloradical complex (spin population at Ru=62%) is essentially the Ru dₓz orbital pointing in the direction of the apical P donor (P3) of the distorted trigonal bipyramid (Figure 4, left). As a result, the spin population of the axial P donor (P3) is significant (ca. 12%; Figure 4, right), thus explaining the observed large HFIs with this donor atom. The two P donors in the distorted equatorial plane bind rather asymmetrically, leading to a larger spin population at one (8%, P2) compared to the other (5%, P1) P donor. The spin population at the connecting P donor trans to the chlorido ligand is small and negative (−0.8%, P4). The resolved HFIs in the experimental X-band EPR spectrum are thus well-explained by the electronic structure of 3. The g-anisotropy of complex 3 is quite small for a metalloradical complex, but this is fully understandable considering the large energy separation (Turbomole, BP86, def2-TZVP) between the dₓz-dominated SOMO and the filled dₓz and dₓz-dominated MOs (1.4 eV and 1.6 eV, respectively).⁸

The small g-anisotropy of 3 allows for recording the isotropic EPR spectrum in THF solution at room temperature (Figure 5). Simulation reveals a gₓz value of 2.047 and HFIs with three equivalent P atoms (Aₓz = 143 MHz). The measured gₓz value is close to the average value of the anisotropic g-tensor components (gₓz = (gₓ + gᵧ + gz)/3 = 2.043). Detection of HFIs with three equivalent P atoms in solution points to rapid positional exchange of the axial and equatorial PPh₃ donors on the EPR timescale. In line with this, the measured Aₓz values measured in solution are close to the averaged values of the resolved anisotropic A-tensor components stemming from the PPh₃ donors measured in frozen solution (Aₓz = Aₓz + Aᵧz + Aₒz = 143 MHz (3 equivalent P atoms), W₉₀ = 25 MHz).

Layering of a THF solution of 3 with pentane resulted in the formation of brown needles suitable for single-crystal X-ray diffraction analysis. The molecular structure (Figure 6) is in good agreement with the EPR data and the DFT-optimized structure. The τ-value of 0.70 confirms a geometry in-between a trigonal bipyramid and a square pyramid.¹¹ The one-electron reduction of 2 to 3 is accomplished by the loss of one chlorido ligand and shortening of most of the Ru–P bonds (Ru–P₁ = 2.2940(12); Ru–P₂ = 2.2930(12) Å) and decrease of the x₁,P₁–Ru–P₂ angle to 134.84(5)° (See the Supporting Information, Table S1).

As one-electron chemical reduction of complex 2 led to the selective formation of the stable Ru′ complex 3, we also explored two-electron reduction of complex 2. Addition of two equivalents of KC₈ to a THF suspension of 2 under N₂ atmos-

Figure 5. Experimental (black) and simulated (red) X-band EPR spectrum of 3 in isotropic solution (THF). Experimental conditions: Temperature 298 K, microwave power 2.0 mW, field modulation amplitude 4 G, microwave frequency 9.3498 GHz. The simulated spectrum was obtained with gₓz = 2.0465, Aₓz = 143 MHz (3 equivalent P atoms), W₉₀ = 25 MHz.

Figure 6. X-ray crystal structure of 3 (CCDC 1555409). Thermal ellipsoids are set at 50% probability. Solvent molecules and hydrogen atoms have been omitted for clarity.
sphere led to formation of the Ru$^0$ dinitrogen complex [Ru$(11)$N$_2j$] (4). IR spectroscopy reveals the presence of an absorption at $v_{N_2} = 2125$ cm$^{-1}$, which indicates the formation of a coordinated dinitrogen ligand that is weakly activated.$^{[12]}$ The $^{31}$P NMR spectrum shows a doublet and a quartet in a 3:1 ratio, both with a coupling constant $J_{P-P}$ of 39 Hz. This coupling is in agreement with a C$_{3v}$-symmetric complex with three equivalent peripheral phosphate atoms that couple with the central P atom in the axial position.

Brick-red colored crystals of 4 suitable for X-ray diffraction were grown by diffusion of pentane into a THF solution of the filtered reaction mixture. The molecular structure confirms formation of complex 4 with dinitrogen coordinated to the ruthenium (Figure 7). Complex 4 has a trigonal bipyramidal geometry (Figure 7).

![Figure 7. X-ray crystal structure of 4 (CCDC 1555410). Thermal ellipsoids are set at 50% probability. Solvent molecules and hydrogen atoms have been omitted for clarity.](image)

Metal orbitals become possible upon decreasing the $\angle$P1–Ru–P2 angle, which is observed in going from 2 (160.04(3)$^\circ$) to 4 (122.85(4)$^\circ$), thus explaining the shortening of the Ru–P1 and Ru–P2 bonds. Moreover, the $\pi$-acidic character of the amino-phosphines P1, P2, and P3 can become dominant over their $\sigma$-donating capacities in the electron-rich Ru$^0$ complex 4.

With the low oxidation state ruthenium complexes 3 and 4 in hand, we decided to explore their reactivity. Both Roper and Grubbs reported the formation of dichlorido Ru$^0$ carbenes upon addition of $\alpha$, $\beta$-dihalide and trihalide compounds to Ru$^0$ complexes, where both the chlorine and the carbene ligands originate from the organohalide.$^{[13]}$ The reaction was proposed to proceed through oxidative addition of the Cl–C bond, followed by $\alpha$-chloride elimination of the Cl–R species yielding the dichlorido ruthenium carbene. However, Ru$^0$ complexes are known to undergo halide atom transfer reactions with organohalides (e.g. catalyzing the Kharash reaction)$^{[14]}$ and thus a radical reaction between complexes 3 or 4 and organohalides could not be excluded. Given our interest in the chemistry of metal-carbene complexes$^{[15,10]}$ we decided to investigate the reaction of the low-valent Ru$^0$ and Ru$^0$ complexes with dichloromethane.

Dissolving 4 in dichloromethane resulted in the formation of 2 as evidenced by in situ $^{31}$P NMR spectroscopy (see the Supporting Information). As no other complexes were detected in the $^{31}$P NMR spectrum, the formation of a metal-carbene intermediate seemed unlikely. We hypothesized that the formation of 2 from 4 could proceed via a radical mechanism in which two chlorine atoms are stepwise abstracted from dichloromethane by the ruthenium complex, leading to two sequential one-electron oxidations of the metal center. This would imply that the Ru$^0$ complex 3 should be an intermediate.

To test this hypothesis, we added two drops of CH$_2$Cl$_2$ to a solution of 3 in [d$_8$]THF. This brown solution turned into a light-brown-colored suspension within 3 days and $^{31}$P NMR spectroscopy indicated clean formation of 2. No signals corresponding to residual 3 were observed by EPR spectroscopy, which indeed shows that 3 can undergo one-electron oxidation through chlorine atom transfer from dichloromethane. Complex 2 is stable in CH$_2$Cl$_2$ or CHCl$_3$. Having established that 2 can be formed by chlorine atom transfer to 3, we investigated whether complex 3 can be formed from 4 by the same type of transformation. When 1 molar equivalent of CH$_2$Cl$_2$ was added to an in situ-generated solution of 4 in THF a strong EPR signal characteristic for formation of 3 was observed after 20 h. This observation indeed points to radical-type reactivity of the closed-shell Ru$^0$ complex 4.

In conclusion, although the formation of Ru$^0$ and Ru$^0$ compounds is rare, we found that the tripodal tetraphosphine scaffold 1 can accommodate ruthenium metal center in the oxidation states Ru$^0$, Ru$^0$, and Ru$^0$. These complexes are sufficiently stable to be isolated and analyzed by X-ray analysis. Initial reactivity studies show that both open-shell Ru$^0$ and closed-shell Ru$^0$ complexes can undergo facile (net) abstraction of a Cl-atom from dichloromethane, resulting in the formation of the corresponding Ru$^0$ and Ru$^0$ complexes 2 and 3. These results show that indole-based tetraphosphorus ligands provide
a useful scaffold to explore the chemistry of low-valent ruthenium species. Future studies should aim at application of these systems in catalytic atom transfer reactions.

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Conflict of interest

The authors declare no conflict of interest.

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