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Metalloradical Reactivity of Ru\textsuperscript{1} and Ru\textsuperscript{0} Stabilized by an Indole-Based Tripodal Tetraphosphine Ligand

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Abstract: The tripodal, tetradentate tris(1-(diphenylphosphophany1)-3-methyl-1H-indol-2-yl)phosphane \textit{PP\textsubscript{3}}-ligand 1 stabilizes Ru in the Ru\textsuperscript{3+}, Ru\textsuperscript{2+}, and Ru\textsuperscript{0} oxidation states. The octahedral [(PP\textsubscript{3})Ru\textsuperscript{3+}(Cl)\textsubscript{3}] (2), distorted trigonal bipyramidal [(PP\textsubscript{3})Ru\textsuperscript{2+}(Cl)\textsubscript{3}] (3), and trigonal bipyramidal [(PP\textsubscript{3})Ru\textsuperscript{0}(N\textsubscript{3})\textsubscript{3}]) (4) complexes were isolated and characterized by single-crystal X-ray diffraction, NMR, EPR, IR, and ESI-MS. Both open-shell metalloradical Ru\textsuperscript{3+} complex 3 and the closed-shell Ru\textsuperscript{0} complex 4 undergo facile (net) abstraction of a Cl atom from dichloromethane, resulting in formation of the corresponding Ru\textsuperscript{2+} and Ru\textsuperscript{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.\textsuperscript{[1]} Ru\textsuperscript{3+} metalloradical complexes are particularly rare\textsuperscript{[2]} and only two types of Ru\textsuperscript{3+} complexes have been successfully isolated thus far. Peters and co-workers reported a five-coordinate 17-electron [Ru\textsubscript{2}N\textsubscript{2}(SiP\textsubscript{3}H\textsubscript{3})\textsubscript{3}] complex supported by an anionic tripodal tetradeinate (SiP\textsubscript{3}H\textsubscript{3})\textsuperscript{-} ligand (SI\textsubscript{P}H\textsubscript{3})\textsubscript{3} = (2-\textit{dipPr\textsubscript{3}PC\textsubscript{6}H\textsubscript{4})\textsubscript{3}Si). Besides Ru\textsuperscript{3+}, this platform also stabilizes complexes in oxidation states ranging from Ru\textsuperscript{3+} to Ru\textsuperscript{0}.\textsuperscript{[3]} Interestingly, the Ru\textsuperscript{3+} complex was shown to catalyze coupling of aryl azides to azoarenes.\textsuperscript{[4]} Recently, the group of Grützmaecher reported the remarkable 4-coordinate 15-electron complex [Ru\textsubscript{2}(tropPP\textsubscript{3}H\textsubscript{2})\textsubscript{3}]BF\textsubscript{4}, featuring two bidentate tropPP\textsubscript{3}H\textsubscript{2} ligands (trop = 5H-dibenz[a,d]cyclo-

Figure 1. Ligand systems capable of stabilizing isolable Ru\textsuperscript{1} species.

First, we aimed at the synthesis of the Ru\textsuperscript{3+} 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)\textsubscript{3}] (2) was readily prepared by reacting stoichiometric amounts of 1 and [Ru(Cl)\textsubscript{3}(C\textsubscript{6}H\textsubscript{5})\textsubscript{3}] in refluxing THF in good yield (Scheme 1).

The \textsuperscript{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 aminophosphine donors...
are equivalent ($\delta = 77.8$ ppm), whereas the third side-arm donor P3 ($\delta = 101.0$ ppm) experiences a different coordination environment. The pivotal, axial phosphine P4 is assigned to the signal at $\delta = 48.5$ ppm. Ru$^1$ complexes with tripodal tetraphosphine ligands often display five-coordination with either square pyramidal or trigonal bipyramidal geometries around the metal center, however in case of complex 2, an octahedral 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 $\angle P_1$-Ru1-P2 of 160.04(3)$^\circ$ (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) Å; Ru1–P4 (2.1932(9) Å) compared to the mutually trans P donors (Ru1–P1 (2.3727(9) Å; Ru1–P2 (2.3189(9) Å)).

To explore the capability of 1 to stabilize low oxidation states of ruthenium, we attempted to determine the Ru$^2$/Ru$^0$ and Ru$^1$/Ru$^0$ reduction potentials of 2. The cyclic voltamogram 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] requires a stronger reducing agent than the previously reported Ru$^1$ complexes [−1.24 V (Ru$^2$/Ru$^1$) and −2.14 V (Ru$^1$/Ru$^0$) for the SiP$_{3i}$Pr$_3$ system in THF; +0.4 V (Ru$^1$/Ru$^0$) for the tropPPh$_2$ complex]. Therefore, we used KC$_8$ to access the desired Ru$^1$ and Ru$^0$ species chemically (Scheme 2).

The addition of one molar equivalent of KC$_8$ 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 Ru$^1$ species formed by one-electron reduction. X-band EPR spectroscopy confirmed the presence of the metal radical species [Ru(1)Cl] (3). The EPR spectrum reveals a rhombic (albeit almost axial) $g$-tensor, characteristic of an $S = \frac{1}{2}$ system (Figure 3). Hyperfine coupling interactions (HFIs) with two P atoms are resolved, in line with previous observations for tripodal tetradeinate phosphine Ru$^1$ complexes.
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.¹⁰

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 d₆z² 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 d₆z²-dominated SOMO and the filled dₓz and dₓy-dominated MOs (1.4 eV and 1.6 eV, respectively).¹¹

The small g-anisotropy of 3 allows for recording the isotropic EPR spectrum in THF solution at room temperature (Figure 5). Simulation reveals a g₁ value of 2.047 and HFIs with three equivalent P atoms (A₁xx = 143 MHz). The measured g₁ value is close to the average value of the anisotropic g-tensor components (g₁ = (g₁ + g₃ + g₅)/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 A₁xx 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 (A₁xx = (A₁xx + A₃xx + A₅xx + A₁yy + A₃yy + A₅yy)/9 = 157 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 accompanied 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 x, 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-

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**Figure 4.** Singly occupied molecular orbital (SOMO; left) and spin density plot (right) of 3 (top view).

**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 g = 2.0465, A₁xx = 143 MHz (3 equivalent P atoms), W = 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.
phere led to formation of the Ru²⁺ dinitrogen complex [Ru²⁺(N₂)] (4). IR spectroscopy reveals the presence of an absorption at \( \nu_{\text{N₂}} = 2125 \text{ cm}^{-1} \), which indicates the formation of a coordinated dinitrogen ligand that is weakly activated. The \(^{31}\text{P}\) NMR spectrum shows a doublet and a quartet in a 3:1 ratio, both with a coupling constant \( J_{\text{P-P}} \) of 39 Hz. This coupling is in agreement with a \( C_2 \)-symmetric complex with three equivalent peripheral phosphine 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, where the metal orbitals become possible upon decreasing the \( \alpha \)-bonding between Ru and P4 attributable to competition for the same metal orbital with the \( \alpha \)-acidic dinitrogen ligand. The general shortening of all Ru–P bonds on progressing from Ru²⁺ via Ru²⁺ to Ru²⁺ in complexes 2, 3, and 4 is somewhat unexpected, as a lower oxidation state of the metal center is intuitively expected to result in weaker binding of \( \alpha \)-donor ligands. The stronger metal–phosphorus interactions observed instead are likely the result of several contributing effects. Going from an octahedral six-coordinate species (Ru²⁺) to a distorted trigonal bipyramidal (Ru²⁺) and a trigonal bipyramidal (Ru²⁺) five-coordinate species lowers the steric hindrance between the phosphorus atoms and allows for better overlap of Ru and P orbitals, resulting in shortening of the Ru–P bonds. Another factor that can play a role is that the P1 and P2 phosphorus donor atoms compete strongly for the same metal orbital as they are in a trans arrangement in complex 2. Binding to separate metal orbitals becomes possible upon decreasing the \( \alpha \)-P1–Ru–P2 angle, which is observed in going from 2 (160.04(3)°) to 4 (122.85(4)°), 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 Ru²⁺ 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 Ru²⁺ carbenes upon addition of \( \alpha \),\( \alpha \)-dihalide and trihalide compounds to Ru²⁺ complexes, where both the chloride and the carbene ligands originate from the organohalides. The reaction was proposed to proceed through oxidative addition of the \( \alpha \)-C bond, followed by \( \alpha \)-chloride elimination of the \( \alpha \)-R species yielding the dichlorido ruthenium carbene. However, Ru²⁺ complexes are known to undergo halide atom transfer reactions with organohalides (e.g. catalyzing the Kharash reaction) and thus a radical reaction between complex 3 or 4 and organohalides could not be excluded. Given our interest in the chemistry of metallocarbenes, we decided to investigate the reaction of the low-valent Ru²⁺ and Ru²⁺ complexes with dichloromethane.

Dissolving 4 in dichloromethane resulted in the formation of 2 as evidenced by in situ \(^{31}\text{P}\) NMR spectroscopy (see the Supporting Information). As no other complexes were detected in the \(^{31}\text{P}\) NMR spectrum, the formation of a metallocarbene 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 Ru²⁺ complex 3 should be an intermediate.

To test this hypothesis, we added two drops of CH₂Cl₂ to a solution of 3 in [d₆]THF. This brown solution turned into a light-brown-colored suspension within 3 days and \(^{31}\text{P}\) 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 CH₂Cl₂ or CHCl₃. 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 CH₂Cl₂ 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 Ru²⁺ complex 4.

In conclusion, although the formation of Ru²⁺ and Ru²⁺ compounds is rare, we found that the tripod tetrathosphate scaffold 1 can accommodate ruthenium metal center in the oxidation states Ru²⁺, Ru³⁺, and Ru⁴⁺. These complexes are sufficiently stable to be isolated and analyzed by X-ray analysis. Initial reactivity studies show that both open-shell Ru²⁺ and closed-shell Ru²⁺ complexes can undergo facile (net) abstraction of a Cl-atom from dichloromethane, resulting in the formation of the corresponding Ru²⁺ and Ru²⁺ complexes 2 and 3. These results show that indole-based tetrathosphate 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.

Keywords: chloride atom abstraction · dinitrogen complexes · metalloradicals · ruthenium · tripodal ligands


CCDC 1555408 (2), 1555409 (3), and 1555410 (4) contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre.

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