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Metalloradical Reactivity of Ru$^1$ and Ru$^0$ Stabilized by an Indole-Based Tripodal Tetraphosphine Ligand

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Abstract: The tripodal, tetradentate tris(1-(diphenylphosphanyl)-3-methyl-1H-indol-2-yl)phosphane PP$_3$-ligand 1 stabilizes Ru in the Ru$^2$, Ru$^1$, and Ru$^0$ oxidation states. The octahedral [(PP)$_3$Ru($^1$)Cl$_2$] (2), distorted trigonal bipyramidal [(PP)$_3$Ru($^0$)Cl] (3) and trigonal bipyramidal [(PP)$_3$Ru($^0$)(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$^1$ complex 3 and the closed-shell Ru$^0$ complex 4 undergo facile (net) abstraction of a SiP$_2$H$_4$ ligand (SiP$_2$ oxidation states. The ligand environment for subsequent reactivity of these complexes is particularly rare and only two types of Ru$^1$ complexes have been successfully isolated thus far. Peters and co-workers reported a five-coordinate 17-electron [Ru$_2$N$_5$(SiP$_2$)$_3$] complex supported by an anionic tripodal tetradentate (SiP$_2$)$_3^-$ ligand (SiP$_2$)$_3^-$= (2-iPr$_2$PC$_6$H$_4$)$_2$Si$.^1$ Besides Ru$^1$, this platform also stabilizes complexes in oxidation states ranging from Ru$^2$ to Ru$^II$.^1$ Interestingly, the Ru$^0$ complex was shown to catalyze coupling of aryl azides to azoarenes.$^1$ Recently, the group of Grützmaecher reported the remarkable 4-coordinate 15-electron complex [Ru(tropPP$_2$)$_2$]BF$_4$ featuring two bidentate tropPP$_2$ ligands (trop=5H-dibenzo[a,d]cyclohepten-5-yl]). Besides Ru$^0$, this ligand scaffold stabilizes ruthenium complexes in oxidation states ranging from Ru$^2$ to Ru$^II$.^1$ No further reactivity with this complex has been reported to date.

Inspired by these intriguing examples, we wondered whether stable metalloradical Ru$^1$ complexes could be accessed in a rigid tripodal PP$_3$ ligand environment for subsequent reactivity evaluation. The above-mentioned Ru$^1$ complexes feature either a strongly δ-donating anionic tripodal (SiP$_2$)$_3^-$ ligand or two neutral π-accepting bidentate (tropPP$_2$) ligands. Hence, we surmised that the use of a tripodal tetradentate ligand featuring both δ-donor and π-accepting phosphorus groups could allow for isolation and reactivity studies of well-defined Ru$^1$ metalloradicals. We turned our attention to the tripodal, tetradentate tris(1-(diphenylphosphanyl)-3-methyl-1H-indol-2-yl)-phosphane ligand (1) (Figure 1), which we previously used to stabilize the metalloradical rhodium complex [Rh$^0$(1)Cl$_{2}$]$_2$. We further wondered whether the corresponding ruthenium(0) complex could also be accessible and if these low-valent species would display interesting reactivity.

First, we aimed at the synthesis of the Ru$^0$ 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$_2$] (2) was readily prepared by reacting stoichiometric amounts of 1 and [Ru(1)(C$_6$H$_5$)$_2$]$_2$ in refluxing THF in good yield (Scheme 1).

The $^{31}$P NMR spectrum of complex 2 displays a triplet of doublets (δ = 101.0 ppm, $J_{ Ph}$ = 26.4, 25.5 Hz), an apparent triplet (δ = 77.8 ppm, $J_{ Ph}$ = 26.5 Hz), and a triplet of doublets (δ = 48.5 ppm, $J_{ Ph}$ = 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

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are equivalent \((\delta = 77.8 \text{ ppm})\), whereas the third side-arm donor \(P3\) \((\delta = 101.0 \text{ ppm})\) experiences a different coordination environment. The pivotal, axial phosphine \(P4\) is assigned to the signal at \(\delta = 48.5 \text{ ppm}\). Ru\(^{II}\) 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 \(2\), 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 \(\mu\)-P1–Ru1–P2 of 160.04(3)\(^\circ\) (See the Supporting Information, Table S1) for the two mutually trans amiphosphines 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)).\(^9\)

To explore the capability of \(1\) to stabilize low oxidation states of ruthenium, we attempted to determine the Ru\(^{II}/Ru^{I}\) and Ru\(^{I}/Ru^{0}\) reduction potentials of \(2\). The cyclic voltammogram of \(2\) in dichloromethane did not show any reduction wave within the solvent window \((E_{\text{red}} = -2.5 \text{ vs. } \text{Fc/Fc}^+\)) and the poor solubility of \(2\) in THF, DMF, acetonitrile, or toluene prevented determination of the reduction potentials of \(2\) below \(-2.5 \text{ V}\). Thus, reduction of complex \(2\) to the desired complex [Ru(1)Cl] (3) requires a stronger reducing agent than the previously reported Ru\(^{I}\) complexes \([-1.24 \text{ V} (\text{Ru}^{II}/\text{Ru}^{I})\] and \(-2.14 \text{ V} (\text{Ru}^{I}/\text{Ru}^{0})\] for the SiP\(_3\) system in THF; \(+0.4 \text{ V} (\text{Ru}^{II}/\text{Ru}^{I})\] and \(-0.3 \text{ V} (\text{Ru}^{I}/\text{Ru}^{0})\] for the tropPPh\(_2\) complex). Therefore, we used KC\(_8\) to access the desired Ru\(^{I}\) 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\(^{I}\) species formed by one-electron reduction. X-band EPR spectroscopy confirmed the presence of the metal-loradical 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 Ru\(^{I}\) complexes.\(^{2c,e,3}\)

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**Scheme 1.** Synthesis of [Ru(1)(Cl)] (2).

**Scheme 2.** Reactivity of 2 with 1 or 2 equiv KC\(_8\) to form 3 or 4, respectively.

**Figure 2.** X-ray crystal structure of 2 (CCDC 1555408). Thermal ellipsoids are set at 50% probability. Solvent molecules and hydrogen atoms have been omitted for clarity.

**Figure 3.** Experimental (black) and simulated (red) X-band EPR spectrum of 3 measured in frozen THF ([Bu\(_4\)N][PF\(_6\)]) was added to obtain an improved glass). Experimental conditions: Temperature 20 K, microwave power 0.063 mW, field modulation amplitude 4 G, microwave frequency 9.3646 GHz. The simulated spectrum was obtained with the parameters shown in Table S2.

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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 d⁶ 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 dxy 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 dxy-dominated SOMO and the filled dxz and dyz-dominated MOs (1.4 eV and 1.6 eV, respectively).[10]

The small g-anisotropy of 3 allows for recording the isotropic EPR spectrum in THF solution at room temperature (Figure 5). Simulation reveals a giso value of 2.047 and HFIs with three equivalent P atoms (Aiso 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 Aiso 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 (Aiso = (A11 + A22 + A33 + A12 + A13 + A23)/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 τ, Ru–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 KCX 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 giso = 2.0465, Aiso 2.143 MHz (3 equivalent P atoms), Wiso = 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.
Phosphine led to formation of the Ru\(^{II}\) dinitrogen complex [Ru(\(^2\)N\(_2\))\(_2\)I\(_2\)] (4). IR spectroscopy reveals the presence of an absorption at \(\nu_{\text{N-N}} = 2125 \text{ cm}^{-1}\), 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\(_5\)-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, with a short Ru–P bond (2.2133(11) \text{ Å}) trans to N\(_2\), which is elongated relative to Ru–P bonds. Moreover, the \(\pi\)-acidic character of the aminophosphines P1, P2, and P3 can be dominant over their electron-donating capacities in the electron-rich Ru\(^{II}\) 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\(^{III}\) carbene upon addition of \(\alpha, \alpha, \alpha\)-trihalide and trihalide compounds to Ru\(^{III}\) complexes, where both the chloride and the carbene ligands originate from the organohalides.\(^{[13]}\) 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\(^{III}\) complexes are known to undergo halide atom transfer reactions with organohalides (e.g., catalyzing the Kharash reaction)\(^{[14]}\) and thus a radical reaction between complex 3 or 4 and organohalides could not be excluded. Given our interest in the chemistry of metallophanes and metallocarbenes\(^{[15,16]}\), we decided to investigate the reaction of the low-valent Ru\(^{II}\) and Ru\(^{III}\) 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 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 Ru\(^{III}\) 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\(^{III}\) complex 4.

In conclusion, although the formation of Ru\(^{II}\) and Ru\(^{III}\) compounds is rare, we found that the tripod tetraphosphine scaffold 1 can accommodate ruthenium metal center in the oxidation states Ru\(^{II}\), Ru\(^{III}\), and Ru\(^{IV}\). These complexes are sufficiently stable to be isolated and analyzed by X-ray analysis. Initial reactivity studies show that both open-shell Ru\(^{II}\) and closed-shell Ru\(^{III}\) complexes can undergo facile (net) abstraction of a Cl-atom from dichloromethane, resulting in the formation of the corresponding Ru\(^{II}\) and Ru\(^{III}\) 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.

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


[16] CCDC 1555408 (2), 1555410 (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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