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Dinuclear Palladium Complexes with Two Ligand-Centered Radicals and a Single Bridging Ligand: Subtle Tuning of Magnetic Properties


Abstract: The facile and tunable preparation of unique dinuclear \([\text{L}][\text{Pd}–\text{X}–\text{Pd}](\text{L})\) complexes \((\text{X} = \text{Cl} \text{ or } \text{N}_2)\), bearing a ligand radical on each Pd, is disclosed, as well as their magnetochemistry in solution and solid state is reported. Chloride abstraction from \([\text{Pd}((\text{NNO})\text{ISQ})]\) \((\text{NNO})\text{ISQ} = \text{iminosequinonato})\) with TIPF\(_6\) results in an unusual monochlorido-bridged dinuclear open-shell diradical species, \([\text{Pd}((\text{NNO})\text{ISQ})\text{Cl}](\text{μ-Cl})]^+\), with an unusually small Pd-Cl-Pd angle (ca. 93°, determined by X-ray). This suggests an intramolecular \(d^6-d^8\) interaction, which is supported by DFT calculations. SQUID measurements indicate moderate antiferromagnetic spin exchange between the two ligand radicals and an overall singlet ground state in the solid state. VT EPR spectroscopy shows a transient signal corresponding to a triplet state between 20 and 60 K. Complex 2 reacts with \(\text{PPh}_3\) to generate \([\text{Pd}(\text{NNO})\text{ISQ})(\text{PPh}_3)]^+\) and one equivalent of \([\text{Pd}((\text{NNO})\text{ISQ})\text{Cl}](\text{μ-Cl})]\). Reacting a 1:1 mixture of \([\text{Pd}((\text{NNO})\text{ISQ})\text{Cl}](\text{μ-Cl})]\) and \([\text{Pd}(\text{NNO})\text{ISQ})\text{Cl}](\text{μ-Cl})]\) furnishes the 1,1-azido-bridged dinuclear diradical \([\text{Pd}((\text{NNO})\text{ISQ})(\text{μ-N}_3\text{N}_2\text{N}_3)]^+\), with a Pd-N-Pd angle close to 127° (X-ray). Magnetic and EPR measurements indicate two independent \(S = 1/2\) spin carriers and no magnetic interaction in the solid state. The two diradical species both show no spin exchange in solution, likely because of unhindered rotation around the Pd–X–Pd core. This work demonstrates that a single bridging atom can induce subtle and tunable changes in structural and magnetic properties of novel dinuclear Pd complexes featuring two ligand-based radicals.

Introduction

Dinuclear transition metal complexes are receiving widespread attention as both structural mimics for naturally occurring metalloenzyme active sites—where metal-metal interactions play an important role in the cooperative activation of small molecules—and for their potential use in bimetallic catalysis. Systems with metal–metal bonds are particularly interesting due to their potential use as electron-reservoirs. A special class are dimers of square-planar \(\text{Rh}^+, \text{Ir}^+, \text{Pt}^+, \text{Pd}^0\) complexes that display (weak) metal-metal bonds due to \(d^6-d^8\) interactions. These interactions arise from overlap in the axial direction between the valence \(d_z^2\) orbitals of the two square planar metal centers, resulting in both filled bonding and antibonding \(d_{\sigma^*}\) orbitals. There is a net overall bonding interaction due to symmetry-allowed mixing with the \((n+1)\) metal \(p_z\) orbitals.

Few dinuclear Pd\(^{\text{II}}\) complexes with intramolecular \(d^6-d^8\) interactions have been identified to date. A bridging acetate or neutral ligand is required to pre-organize both metals for this bonding interaction to occur, but an unsupported Pd–Pd interaction has also been reported. However, dinuclear palladium complexes bridged by a single donor ligand are scarce and none featuring an intramolecular \(d^6-d^8\) interaction have been reported to the best of our knowledge (Figure 1).

Redox-active ligands have recently emerged as an attractive strategy to provide necessary redox equivalents for bond-activation and bond-formation processes. As a logical extension, dinuclear transition metal complexes containing redox-active ligand radicals are receiving significant attention lately.
Scheme 1. Redox states of Pd$^\text{II}$-coordinated NNO ligand.

Results and Discussion

Synthesis and characterization of dinuclear Pd complex 2 in solution

Abstraction of the chlorido ligand in complex 1 with Ag salts resulted in one-electron oxidation of the ligand backbone to give diamagnetic cationic [PdCl(NNO)$^{\text{II}}$]$^+$ species (Scheme 1).

Treatment of 1 with the soffer, non-oxidizing thallium(l) hexafluorophosphate (TlPF$_6$) in a non-coordinating solvent (CH$_2$Cl$_2$) led to a color change from brown to brownish-green (Scheme 2). CSI-MS studies indicate the presence of an intact dinuclear species in solution with $m/z$ 923.2468 [$M^+$], indicating the formation of diradical 2. Notably, addition of up to five equivalents of TIPF$_6$ resulted in the same product, with no indication for additional chloride abstraction. Dark-brown single crystals of 2 suitable for X-ray structure determination were obtained by diffusion of pentane into a CHCl$_3$ solution.

The molecular structure (Figure 2) exhibits slightly distorted square-planar geometries around both metal centers and a single bridging chlorido ligand. Well-defined dinuclear palladium complexes with just a single chlorido bridging ligand are
and no examples bearing ligand radicals have been reported. The intra-ligand bond lengths are characteristic for the iminosemiquinonato (NNO) oxidation state for both ligands. The two Pd–Cl bond lengths are similar and slightly longer than for complex 1. Most noteworthy is the very small Pd–Cl–Pd angle of 93.11(2), which hints at an interaction between the two {Pd(NNO)} fragments. Other crystallographically characterized dinuclear (Pd₂(μ-Cl)) species have much larger Pd–Cl–Pd angles of 120–130°. The short Pd–Pd distance of 3.408(3) Å is longer than the sum of the van der Waals radii (3.26 Å), ruling out a formal bond. The torsion angle of 66° between the two {Pd(NNO)} segments seems to rule out any involvement of π–π stacking between the ligands, but rather suggests the existence of a d²–d² interaction.

To find an explanation for the unusually skewed [LPd₂(Cl)PdL] geometry, complex 2 was studied computationally by using DFT calculations (Figure 3, top). It was found that dispersion corrections were essential to obtain structures that were in good agreement with the experimental data (Figure 3, middle). This is in agreement with earlier reports which also state that d²–d²-type interactions are best described as dispersion interactions. Employing either i) the b3-lyp-D3 functional with the def2-TZVP basis-set or ii) the PBE0-D3 functional with the 6-31+G(d,p) basis-set for light atoms and the LanL2DZ-mod basis-set for Pd afforded a geometry in agreement with the experimental parameters. Notably, where the b3-lyp-D3/def2-TZVP combination slightly overestimated the Pd–Pd distance (α) and the Pd-Cl-Pd angle (β), the PBE0-D3/6-31+G(d,p)/LanL2DZ-mod combination slightly underestimated both. AIM analysis showed no formal bond between the Pd atoms, but it provided support for a possible interaction involving d orbitals. The CPK model of the optimized structure (Figure 3, bottom) suggests a close contact between one tBu group of fragment and one of the gem-Me groups of the second fragment. To exclude that the respective van der Waals interaction is the sole contributor to the short intramolecular Pd–Pd distance, the structure was optimized with the tBu groups removed. Analysis of the resulting structure showed a shortening of the Pd–Pd distance suggesting that the steric bulk of the tert-butyl groups actually weakens any interaction between the two d² metal centers.

The open-shell singlet (OSS) and the (optimized) triplet state lie very close in energy (ΔE_OSS – ΔE_T = −0.3 kcal mol⁻¹), indicative of a moderate spin-exchange interaction (2J_{calc} = −106.1 cm⁻¹; b3-lyp-D3/def2-TZVP). In both the OSS and triplet state, both unpaired electrons reside on separate iminosemiquinonato fragments (Figure 4, left). Analysis of the molecular orbitals clearly indicates a weak bonding overlap between the d₈ orbitals of the two metal centers (Figure 4, right). Indeed, as is common for d₈–d₈ interactions, a weakly antibonding orbital (ca. 0.25 eV higher in energy) is also filled. Natural bond order (NBO) analysis showed a bonding interaction of approximately 6 kcal mol⁻¹.

<table>
<thead>
<tr>
<th>Bond</th>
<th>NNOpd1</th>
<th>NNOpd2</th>
</tr>
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<tbody>
<tr>
<td>C1–C2</td>
<td>1.426(4)</td>
<td>1.424(4)</td>
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<tr>
<td>C2–C3</td>
<td>1.373(4)</td>
<td>1.373(4)</td>
</tr>
<tr>
<td>C3–C4</td>
<td>1.427(5)</td>
<td>1.424(5)</td>
</tr>
<tr>
<td>C4–C5</td>
<td>1.373(4)</td>
<td>1.369(5)</td>
</tr>
<tr>
<td>C5–C6</td>
<td>1.421(4)</td>
<td>1.428(4)</td>
</tr>
<tr>
<td>C6–C1</td>
<td>1.447(4)</td>
<td>1.450(4)</td>
</tr>
<tr>
<td>C1–O1</td>
<td>1.321(4)</td>
<td>1.318(3)</td>
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<tr>
<td>C8–N1</td>
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<td>Pd–N1</td>
<td>1.919(3)</td>
<td>1.928(3)</td>
</tr>
<tr>
<td>Pd–O1</td>
<td>1.987(2)</td>
<td>1.984(2)</td>
</tr>
</tbody>
</table>
Magnetic behavior of complex 2 in the solid state

For a definitive insight into the magnetic behavior of complex 2, magnetic measurements were performed on a polycrystalline sample using a SQUID magnetometer. The $\chi_m T$ value at room temperature is approximately 0.6 cm$^3$ mol$^{-1}$ K, corresponding to an effective magnetic momentum of 2.19 $\mu_B$. Upon lowering the temperature, $\chi_m T$ approaches to zero, revealing a singlet ground state. The $\chi_m$ vs. $T$ plot (Figure 5, inset) exhibits a broad maximum at 110 K, again indicating an antiferromagnetic (AF) interaction. Modeling the experimental data using a fitting procedure to the Heisenberg–Dirac–van Vleck (HDvV) spin Hamiltonian for isotropic exchange coupling and Zeeman splitting (Eq. (1)) leads to an exchange coupling constant $J$ of ~63 cm$^{-1}$.

$$\hat{H} = -2JS_1S + g\mu_B\vec{B}(S_1 + S_2)$$

Therefore the singlet–triplet energy gap $\Delta E_{S-T}$ (which is equal to $2J$) is $-126$ cm$^{-1}$ or $-0.36$ kcal mol$^{-1}$, confirming a singlet ground state for 2 with a moderate spin-exchange interaction. These observations are fully supported by the DFT calculations, predicting a similarly moderate AF exchange coupling constant (ORCA, b3-lyp, def2-TZVP, D3ZERO: $-45.3$ cm$^{-1}$; Turbomole, b3-lyp, def2-TZVP, disp3: $-53.1$ cm$^{-1}$).

VT EPR spectroscopy on a polycrystalline sample of 2 is in agreement with the SQUID measurement revealing a triplet signal in the temperature range between 20–60 K (Figure 6). At temperatures >60 K the signal broadens and rapidly becomes very weak due to fast relaxation (likely induced by Pd).[20] Below 60 K the intensity of the triplet signal shows the typical temperature dependence expected for an AF coupled system, and the signal vanishes completely at temperatures below 20 K (Figure 6). Fitting the temperature dependence of the triplet signal intensity versus T yielded an exchange coupling parameter $J = -47$ cm$^{-1}$, similar to the DFT-calculated value ($J = -45$ cm$^{-1}$) and the value obtained from the SQUID measurements ($J = -63$ cm$^{-1}$).[20]

**Magnetic behavior complex 2 in solution**

Interestingly, in solution there is no evidence for exchange coupling between the two unpaired electrons of complex 2. Contrary to the solid state data, the EPR spectrum of 2 in rapidly frozen toluene at 20 K shows only a $S = \frac{1}{2}$ signal, reflecting a more random orientation of the two Pd subunits than in the crystalline solid state. In benzene solution at room temperature, a well-resolved $S = \frac{1}{2}$ signal is observed, with similar hyperfine couplings as previously observed for 1 (Figure 7 and the Supporting Information). Magnetic susceptibility measurement of 2 at 298 K in CDCl$_3$ using Evans’ method[21] gave an effective magnetic moment ($\mu_{\text{eff}}$) of 2.18 $\mu_B$, which is close to the value predicted for a system with two noninteracting $S = \frac{1}{2}$

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Figure 5. Temperature dependence of $\chi_m T$ and $\chi_m$ (inset) of complex 2. The solid lines show the simulated data and the empty squares the experimental data.

Figure 6. Detection of the triplet signal of 2 and its temperature dependence (20–60 K range).

Figure 7. Experimental and simulated EPR spectrum of complex 2 in benzene solution. Experimental parameters: Freq = 9.368164 GHz, $T = 298$ K, Mod Ampl. = 1, power = 2 mW. Parameters used in the simulation: $A^{H_1} = 12.5$ MHz, $A^{H_2} = 23.3$ MHz, $A^{\text{iso}} = 11.0$ MHz, $A^{\text{iso}} = 2.2$ MHz.
spins (2.45 $\mu_\text{B}$). The UV/Vis spectrum of 2 in solution is similar to that of 1, with an additional absorption at 441 nm.

Paramagnetic 2 shows relatively sharp resonances in the $^1$H NMR spectrum at $\delta = -2$–20 ppm at room temperature.[20] VT NMR spectroscopy of 2 in CDCl$_3$ showed a temperature dependence for the $^1$H NMR chemical shifts. Increasing the temperature from −60 to +60°C led to a narrowing of the spectral range by ±8 ppm. Plots of the $^1$H NMR shifts versus $T^{-1}$ are shown in Figure 8. The linear dependence of the paramagnetic shift with $T^{-1}$ over this temperature range for all seven observable proton types (one signal is obscured by the tBu group) allowed for tentative assignment of the observed resonances.[20] The linear Curie plots reveal an uncomplicated spin state with no sign of exchange coupling in solution in this temperature range. The linearity of these plots, combined with the fact that no additional NMR signals are generated over the temperature range from −60 to +60°C (dissociation of the dinuclear complex should result in additional further indicates that the dinuclear complex stays intact in solution over this broad temperature range. These observations confirm that in solution the two unpaired electrons of 2 behave as essentially non-interacting spin carriers over a broad temperature range. Hence, the magnetic behavior of this complex in solid state and solution phase is very different, which is likely related to rotational flexibility in the Pd-Cl-Pd core (Figure 9). HR-MS data also support the proposal that 2 remains intact as a dinuclear species in solution.

Reactivity of dinuclear Pd complex 2

To confirm whether this novel dinuclear diradical species only forms in the absence of suitable donor ligands, complex 2 was treated with one equivalent of PPh$_3$.[22] This led selectively to paramagnetic complex 3, together with one equivalent of complex 1 (Scheme 3). This result confirms that the chlorido-bridged dinuclear complex, although stable, does not persist in the presence of a better ligand. It also suggests that it might be possible to exchange bridgehead groups in case a non-neutral co-ligand is employed. When a solution of complex 1 in CH$_2$Cl$_2$ is treated with an equimolar amount of TIPF$_6$ in the presence of PPh$_3$, complex 3 is formed as the only product with full conversion of 1. Notably, $^{31}$P NMR spectroscopy on paramagnetic 3 reveals the coordinated phosphine as a sharp singlet at $\delta = 28.63$ ppm (the chemical shift is indicative of coordination to Pd)[23] and the PF$_6$ anion as a fully resolved septet, while the $^1$H NMR spectrum displays four broad resonances between $\delta = 8.36$ and 1.19 ppm.

Although it appears that dinuclear 2 is susceptible to reaction with additional ligand and potentially also metalloligand species, we reasoned that access to other mononuclear bridged dinuclear palladium diradical species could be more easily achieved by using a mixture of chloride species 1 and a neutral, non-chloride-containing analogue, [Pd(X)(NNO)]$.^6$. The in situ-generated cationic [Pd(NNO)$^6$]$^-$ species should then be trapped selectively by this non-chlorido derivative to form a new mononuclear-bridged dinuclear diradical. Therefore, the azido derivative was prepared by substitution of the chlorido ligand in 1 through salt metathesis with sodium azide. The reaction proceeded smoothly in MeOH, yielding the corresponding [Pd(N$_2$)(NNO)$^6$]. The IR spectrum contains a strong absorption at $\nu = 2035$ cm$^{-1}$, which is in the characteristic range for metal azides. Cyclic voltammetry of 4 in CH$_2$Cl$_2$ solution revealed fully reversible one-electron oxidation and reduction events at +0.07 V and −0.97 V vs. Fc/Fc$^+$, respectively. The observed redox potentials reflect the higher electron-withdrawing character of the azido, relative to the chlorido ligand in complex 1 (−0.04 and −1.1 V),[33] showing that the redox behavior of the NNO ligand is also strongly dependent on the additional ligand. Similar to 1, in situ reduction using [Co(Cp)$_2$]$^-$ allowed for the formation of a diamagnetic species which could be characterized by NMR spectroscopy.[20] Crystals for neutral azido-species
showed a strong absorption at 2073 cm\(^{-1}\) that can be attributed to a palladium azide fragment, although this signal is clearly shifted to a higher wavenumber than found for \(4\) (\(\Delta\nu = 38\) cm\(^{-1}\)).

Dark yellowish-green needles suitable for X-ray diffraction were obtained by slow diffusion of pentane into a chloroform solution (Figure 11), which unambiguously confirmed the composition of complex \(5\) as \([\text{Pd}(\text{NNO})\text{N}]_2\)\{(N\(^\circ\)N\(^\circ\)N\(^\circ\)N\(^\circ\))\}PF\(_6\). The metric parameters for the intramolecular bond lengths are characteristic for the iminosemiquinonato oxidation state for both NNO ligands, just as in complex \(2\). Due to the 1,1-bridging mode of the azide, the Pd–N\(_{\text{N}}\) bonds are slightly elongated with respect to \(4\). The elongated Pd–Pd distance of 3.6843(3) Å and the large Pd-N-Pd angle of approximately 127° contradict the presence of a d\(^5\)–d\(^5\) interaction between the two metal centers, which is in stark contrast with what is observed for complex \(2\). Another interesting observation is the elongation of the N\(_{\text{N}}\)–N\(_{\text{N}}\) bond compared to the value in \([\text{Pd}(\text{N})\text{NNO})\text{N}]_2\)\{(N\(^\circ\)N\(^\circ\)N\(^\circ\)N\(^\circ\))\}\{\(\text{PF}_6\)\} (1.225(12) Å vs. 1.168(2) Å for \(4\)) and a slight contraction of the N\(_{\text{N}}\)–N\(_{\text{N}}\) bond (1.148(13) Å vs. 1.168(3) Å for \(4\)), which is suggestive of azide activation.

The EPR spectrum of \(5\) at room temperature is similar to those of \(1\) and \(2\). EPR spectroscopy on a polycrystalline sample showed no triplet signal at both ambient and low temperatures. Notably, magnetic susceptibility measurements on the same solid (Figure 12, squares) showed a nearly temperature-independent \(\chi\) value of 0.757 cm\(^3\) mol\(^{-1}\) K\(^{-1}\) (corresponding to 2.46 \(\mu_B\)), as expected for two independent \(S = \frac{3}{2}\) spin carriers (2.45 \(\mu_B\) with no significant magnetic interaction. Hence, the magnetic behavior is similar to that of \(1\) (Figure 12, rounds), where no intramolecular spin-exchange is possible by default.

### Conclusions

In conclusion, chloride abstraction from \(1\) in the absence of a suitable additional ligand results in the formation of the unique mono-chloride bridged dinuclear diradical \(2\), wherein the separated unpaired electrons are located on the redox-active NNO ligands. Single crystal X-ray crystallography indi-
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Figure 12. Temperature dependence of \( \chi_M(T) \) of complex 1 (circles) and complex 5 (squares).

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