

Dinuclear Palladium(III) Complexes

Dinuclear Palladium(III) Complexes with a Single Unsupported Bridging Halide Ligand: Reversible Formation from Mononuclear Palladium(II) or Palladium(IV) Precursors**

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Along with the well-known involvement of Pd⁰ and Pd^{II} oxidation states in a large number of palladium-catalyzed reactions,^[1] recent reports have proposed the intermediacy of less-common Pd^{IV} and Pd^{III} oxidation states in several chemical transformations.^[2] Among these systems, dinuclear and mononuclear Pd^{III} complexes have been shown to act as active intermediates in both two- and one-electron oxidative C–H functionalization and C–C bond formation reactions.^[3–6] For example, dinuclear organometallic Pd^{III} complexes stabilized by a Pd–Pd bond have been recently reported^[3,7] and shown to be a catalytically competent alternative to mononuclear Pd^{IV} species in carbon–heteroatom bond-formation reactions.^[3,4] In this context, we have recently shown that mononuclear Pd^{III} complexes stabilized by a tetradentate diazapyridinophane ligand can be isolated and have shown that they exhibit C–C bond-formation reactivity.^[6] Continuing our work in the study of high-valent Pd complexes, we report herein novel cationic dinuclear Pd^{III} and mononuclear Pd^{IV} complexes supported by a common tridentate nitrogen-donor ligand, *N,N,N'*-trimethyl-1,4,7-triazacyclononane (Me₃tacn). Moreover, we provide evidence for the involvement of a Pd^{III} species in the Kharasch addition reaction and confirm the ability of Pd to catalyze one-electron radical reactions. In addition, the reported Pd^{III} systems are the first group 10 d⁷–d⁷ dinuclear complexes bridged by a single unsupported halide ligand and represent a model of the delocalized Pd^{III}–X–Pd^{III} electronic structure that has been proposed to exist in some –Pd–X–Pd–X– one-dimensional (1D) chains.^[8]

While triazacyclonane (tacn)^[9,10] and other tacn derivatives^[11] have been employed in the synthesis of Pd complexes, only one complex, [(Me₃tacn)Pd^{II}(MeCN)₂](PF₆)₂, has been reported for Me₃tacn.^[10] We have synthesized the Pd^{II} complexes [(Me₃tacn)Pd^{II}X₂] (X = Cl **1a**, X = Br **1b**) through

the reaction of Me₃tacn with [(MeCN)₂Pd^{II}X₂].^[12] The X-ray structure analysis of **1a** reveals a square-planar arrangement of two Cl[–] ions and two N atoms around Pd, while the third N atom of Me₃tacn is not in close proximity to the metal center (Figure 1a),^[13] in contrast to the five-coordinate geometry

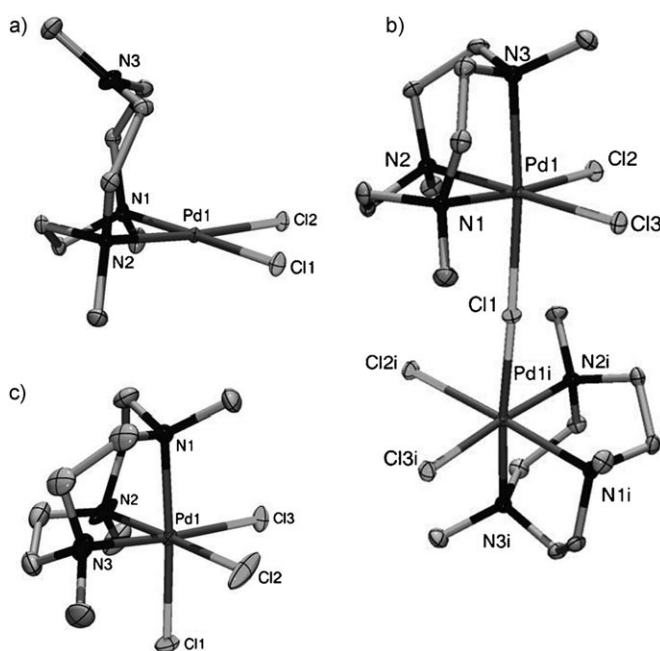


Figure 1. ORTEP representation (ellipsoids set at 50% probability) of a) **1a**, b) the cation of **2a**, and c) the cation of **3a**. Selected bond distances [Å] and angles [°]: **1a**: Pd1–N1 2.0736(5), Pd1–N2 2.0878(5), Pd1–Cl1 2.30651(18), Pd1–Cl2 2.32102(17). **2a**: Pd1–N1 2.094(2), Pd1–N2 2.105(2), Pd1–N3 2.273(2), Pd1–Cl2 2.3179(7), Pd1–Cl3 2.3224(7), Pd1–Cl1 2.4801(2), Cl1–Pd1i 2.4801(2), Pd1–Pd1i 4.931; Pd1–Cl1–Pd1i 167.47(4). **3a**: Pd1–N3 2.080(8), Pd1–N1 2.0806(16), Pd1–N2 2.093(8), Pd1–Cl1 2.302, Pd1–Cl2 2.308, Pd1–Cl3 2.308.

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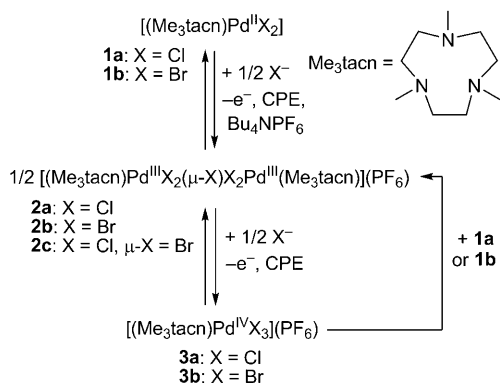
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observed for [(Me₃tacn)Pd^{II}(MeCN)₂](PF₆)₂.^[10] Cyclic voltammetry (CV) of both **1a** and **1b** in MeCN/Bu₄NPF₆ reveals two closely-spaced waves at 0.05–0.17 V versus Fc^{+/0}/Fc and additional waves at higher potentials, suggestive of oxidatively induced chemical reactions.^[12,14]

Controlled potential electrolysis (CPE) at 0.3–0.4 V for both **1a** and **1b** leads to formation of a dark purple species in 60–70% yields of isolated product after passing a charge corresponding to a one-electron oxidation. X-ray-quality crystals of the electrooxidation products obtained from MeCN/Et₂O reveal the formation of dinuclear complexes

$[(\text{Me}_3\text{tacn})\text{Pd}^{\text{III}}\text{X}_2(\mu\text{-X})\text{Pd}^{\text{III}}\text{X}_2(\text{Me}_3\text{tacn})](\text{PF}_6)$ ($\text{X} = \text{Cl}$ **2a**, $\text{X} = \text{Br}$ **2b**), in which a single halide ion bridges the two Pd centers (Scheme 1 and Figure 1b; Supporting Information,



Scheme 1. Electrochemical synthesis of dinuclear Pd^{III} complexes and their interconversion to mononuclear Pd^{III} and Pd^{IV} complexes.

Figure S31).^[13,15] Each metal center has a distorted octahedral geometry with two N atoms and the two terminal halides in the equatorial plane, while the third N atom of Me₃tacn and the bridging halide occupy the axial positions. The coordination geometry of Pd atoms and the overall charge of the dimer confirm the presence of Pd^{III} centers. To the best of our knowledge, complexes **2a** and **2b** are the first dinuclear Pd^{III} complexes that are not stabilized by a Pd–Pd bond.^[3,7] Furthermore, this result suggests that stabilization of the Pd^{III} oxidation state can also be achieved by a tridentate N-ligand and does not require a rigid tetradentate ligand.^[6]

The formation of dinuclear Pd^{III} complexes **2a** and **2b** from the mononuclear precursors **1a** and **1b** is intriguing. The circa 65% yield of product suggests that the bridging halide ion comes from another molecule of the Pd^{II} precursor.^[16] Indeed, addition of 0.5 equiv of external halide leads to a simpler CV that shows only two closely spaced oxidative waves (Table 1; Supporting Information Figures S1–S4), and CPE at 0.3–0.4 V leads to formation of dark purple complexes **2a** and **2b** in higher yields (ca. 80%).^[12,17] Interestingly, when Br[−] was added to a solution of **1a**, the mixed halide complex $[(\text{Me}_3\text{tacn})\text{Pd}^{\text{III}}\text{Cl}_2(\mu\text{-Br})\text{Pd}^{\text{III}}\text{Cl}_2(\text{Me}_3\text{tacn})](\text{PF}_6)$ (**2c**) formed (Scheme 1), as confirmed by X-ray crystallography (Support-

Table 1: Spectroscopic properties of dinuclear Pd^{III} complexes **2a–c**.

Complex	$E_{1/2}^{\text{III/III}}$, $E_{1/2}^{\text{III/IV}}$ [mV] ^[a]	UV/Vis (MeCN) λ [nm] (ϵ [L mol ^{−1} cm ^{−1}])
2a	55, 163	534 (21 000), 449 (sh, 4900), 360 (6100), 260 (43 000)
2b	45, 171	570 (25 000), 411 (8900), 273 (47 000)
2c	65, 174 ^[b]	546 (17 000), 378 (6800), 262 (41 000)

[a] Potentials vs. Fc⁺/Fc are measured by differential pulse voltammetry (DPV) for solutions of **1a** or **1b** in the presence of 1 equiv of Cl[−] or Br[−], respectively, in 0.1 M Bu₄NPF₆/MeCN. Complexes **2a–c** show two oxidation waves at similar potentials (see the Supporting Information). [b] Potentials are measured by DPV for a solution of **1a** in the presence of 1 equiv of Br[−].

ing Information, Figure S31).^[12] This observation suggests that the use of alternate exogenous ions can lead to Pd^{III} complexes with bridging ligands and altered electronic properties.^[18] Complexes **2a–c** are structural models of the dinuclear unit found in $-\text{M}-\text{X}-\text{M}-\text{X}-$ 1D extended chains^[8] in the average-valent Mott–Hubbard (MH)^[8,19] state M^{III}–X–M^{III} (that is, a Robin–Day class III state).^[20] The bridging halide ligand in **2a–c** is located at the midpoint between the two metal centers,^[21] while the short Pd···Pd distances (**2a** 4.931 Å, **2b** 5.133 Å, **2c** 5.031 Å, Figure 1b; Supporting Information, Figure S31)^[22] suggest an intimate orbital overlap between Pd and the bridging halide that is supported by the observed strong antiferromagnetic coupling between the unpaired d_{z²} electrons of the two Pd^{III} centers,^[23] which is typical for a delocalized MH state.^[8,19b]

The UV/Vis spectra of complexes **2a–c** in MeCN reveal at least three intense absorption bands at 535–570 nm, 360–410 nm, and 260–280 nm, respectively (Table 1 and Figure 2).^[24] Density functional theory (DFT) and time-

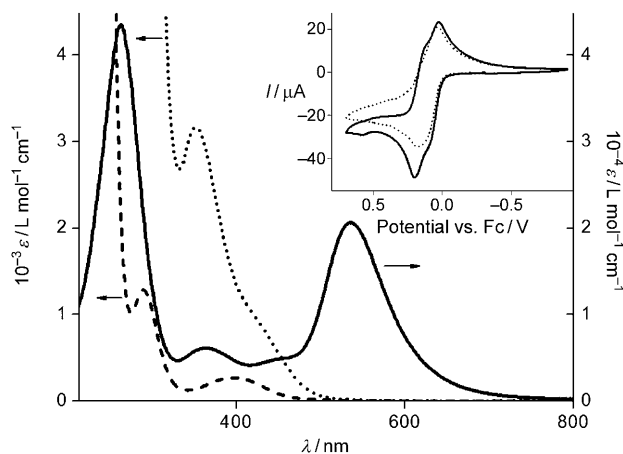


Figure 2. UV/Vis spectra of **1a** (----), **2a** (—), and **3a** (.....) in MeCN. Inset: CV of **1a** in the presence of 0.5 equiv Cl[−] (.....) and 1 equiv Cl[−] (—) in 0.1 M Bu₄NPF₆/MeCN.

dependent DFT (TD-DFT) calculations were employed in the assignment of these transitions. For **2a**, the 534 nm band exhibits an uncommonly large extinction coefficient ($\epsilon = 21\,000 \text{ L mol}^{-1} \text{ cm}^{-1}$) and is assigned to an intermetallic Pd-to-Pd charge transfer (MMCT)^[25] transition that is strongly mixed with a $\mu\text{-Cl}$ -to-Pd CT transition (LMCT).^[26] A similar assignment has been proposed for the low-energy transitions in Pd^{III}–X–Pd^{III}–X 1D chains.^[8] TD-DFT calculations support such an assignment by revealing a large oscillator strength for the HOMO to LUMO+1 MMCT transition, where the HOMO exhibits σ -bonding Pd– $\mu\text{-Cl}$ character and the LUMO+1 has antibonding Pd– $\mu\text{-Cl}$ character (Figure 3). Furthermore, the higher-energy bands can be assigned to a combination of bridging and terminal halide-to-Pd LMCT bands (for example, HOMO–10 and HOMO–12 to LUMO+1, respectively; Figure 3), as suggested previously^[8] and supported by TD-DFT calculations.^[12] As expected, the replacement of Cl[−] with Br[−] ligands for **2a** to **2c** to **2b** leads to

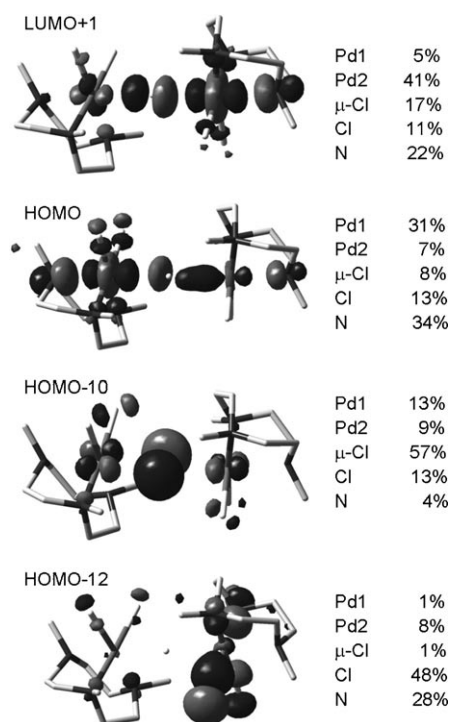


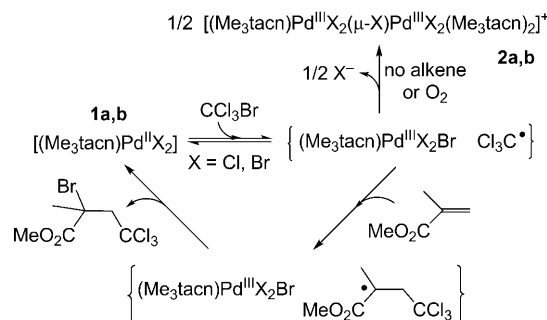
Figure 3. DFT-calculated (UB3LYP/CEP-31G) molecular orbitals (MOs) of **2a** that are proposed to be involved in the observed UV/Vis absorption bands. The calculated atomic contributions are listed for each MO (Pd1 and Pd2 represent the left and the right metal center, respectively, μ-Cl is the bridging Cl⁻ ligand, Cl refers to the terminal Cl⁻ ligands, and N to the N atoms).^[12]

lower energies of all transitions and thus supports the halide contributions to the corresponding MOs.^[19b]

CV studies show that addition of one equivalent of halide to **1a** and **1b** leads to an increase of the peak current corresponding to the second oxidation wave (Figure 2, inset). CPE of **1a** at about 0.5 V versus Fc⁺/Fc in the presence of 1 equiv of Cl⁻ led to the appearance of an intense band at 534 nm associated with the dinuclear species **2a**, followed by its complete disappearance to give a yellow solution after a two-electron oxidation (Figure 2).^[12] While the yellow species is unstable at RT, it leads to formation of yellow crystals at -20 °C in MeCN/Et₂O. The crystal structure reveals a cationic mononuclear Pd^{IV} complex, [(Me₃tacn)Pd^{IV}Cl₃](PF₆) (**3a**; Scheme 1); a similar complex [(Me₃tacn)Pd^{IV}Br₃](PF₆) (**3b**) is obtained upon CPE of **1b** in the presence of 1 equiv of Br⁻, both **3a** and **3b** exhibiting a pseudo-octahedral geometry around the Pd center (Figure 1c; Supporting Information, Figure S38).^[12,27] The Pd^{II}/Pd^{III}/Pd^{IV} interconversions are reversible: electrochemical reduction of the mononuclear species **3a** (or **3b**) at -0.3 V versus Fc/Fc⁺ occurs via the intermediate dinuclear complex **2a** (or **2b**) to eventually produce the mononuclear species **1a** (or **1b**). Interestingly, complexes **3a,b** are unstable and slowly decay to the corresponding Pd^{III} species **2a,b**; moreover, a rapid reaction occurs when 1 equiv of the Pd^{II} complex **1a** (or **1b**) is added to a solution of **3a** (or **3b**) to generate the dinuclear Pd^{III} complex **2a** (or **2b**) in quantitative yield. These studies suggest that the Pd^{III} complexes **2a,b** are more stable under

ambient conditions than either the corresponding Pd^{IV} species or a Pd^{II}/Pd^{IV} mixture that is equivalent to a mixed-valence Pd^{IV}-X-Pd^{II} species. This result is in contrast to the use of extreme conditions^[8] or Pd-to-Ni substitution^[19c,d] required for the generation of the Pd^{III}-X-Pd^{III} state in 1D chains. Furthermore, the interconversion between dinuclear Pd^{III} and mononuclear Pd^{IV} species parallels the proposed involvement of analogous intermediates in Pd-catalyzed C-H oxidative functionalization reactions and suggests that for a given ligand environment both types of intermediates can be present.^[3-6]

The relatively low oxidation potentials of complexes **1a,b** have prompted us to investigate their reactivity in one-electron redox reactions, such as the Kharasch addition of polyhaloalkanes to alkenes.^[28] Both **1a** and **1b** exhibit catalytic activity in the addition of CCl₃Br to a number of alkenes (methyl methacrylate, methyl acrylate, styrene, norbornene, cyclopentene) to give selectively the 1:1 addition product in good to high yields at 65 °C under N₂ (Supporting Information, Chart S1, Table S1).^[12] Kinetic studies of the CCl₃Br addition to methyl methacrylate (MMA) catalyzed by **1a** reveal a first-order dependence on **1a** and MMA concentration and a saturation behavior with respect to CCl₃Br concentration, thus suggesting a mechanism that involves a reversible electron transfer/halogen transfer from CCl₃Br to Pd^{II} to form a Pd^{III} species and a Cl₃C[•] radical that subsequently reacts with the alkene and leads to the addition-product formation (Scheme 2).^[28] While no Pd^{III}



Scheme 2. Proposed mechanism for the Kharasch reaction catalyzed by **1a,b** and the formation of the dinuclear Pd^{III} complexes **2a,b**.

intermediate was observed under optimal catalytic conditions, the dinuclear complex **2a** was detected by UV/Vis at RT, both in absence and in presence of MMA (Supporting Information, Figure S24).^[29] Moreover, a higher yield of **2a** (or **2b**) was obtained when **1a** (or **1b**) was reacted with CCl₃Br in presence of O₂, a known radical trap that can react with the Cl₃C[•] radical^[30] and thus drive the formation of the dinuclear Pd^{III} species. As the catalytic reaction rate shows a first-order dependence in catalyst concentration, and the complex **2a** was not observed under optimal catalytic conditions, the formation of the dinuclear Pd^{III} complex is most likely a means of stabilizing the transient mononuclear Pd^{III} intermediate (Scheme 2).^[12] Moreover, the observed chemical oxidation of **1a,b** to form **2a,b** suggests that the polyhaloal-

kane acts as both the oxidant and the halogen-atom donor and thus parallels the electrosynthesis of complexes **2a,b** through electrochemical oxidation in presence of an external halide (Scheme 1).^[31]

In conclusion, we have presented herein the synthesis and characterization of stable dinuclear Pd^{III} complexes formed by oxidation of mononuclear Pd^{II} precursors. Effective stabilization of the Pd^{III} oxidation state was accomplished using the common tridentate ligand Me₃tacn and halide ions and does not require the formation of a Pd^{III}–Pd^{III} bond. Moreover, these dinuclear Pd^{III} complexes seem to be more stable than the corresponding mononuclear Pd^{IV} (and Pd^{III}) complexes under an analogous ligand environment. These results support our hypothesis that Pd^{III} complexes are more common than previously anticipated and can play important roles in various Pd-catalyzed reactions. Furthermore, we suggest that under a given ligand environment, the involvement of either Pd^{III} or Pd^{IV} species as reactive intermediates cannot be unambiguously ruled out or confirmed, given their facile interconversion. Moreover, the reported dinuclear Pd^{III} complexes are models of the delocalized Pd^{III}–X–Pd^{III} electronic structure found in Group 10 M–X–M–X 1D extended chains. Current research efforts are aimed at characterizing the reactivity and electronic properties of these unique dinuclear systems.

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- [14] Coulometry measurements confirm that both oxidations correspond to one electron processes (see the Supporting Information).
- [15] The presence of dimers **2a** and **2b** in solution was confirmed by ESI-MS and the lack of an EPR signal for the corresponding solutions at 77 K or RT.
- [16] The presence of [(Me₃tacn)PdCl(MeCN)]⁺ in solution after one-electron oxidation of **1a** was detected by CV and confirmed by independent synthesis (see the Supporting Information). If (Me₃tacn)PdCl(MeCN)⁺ is the only halide abstraction product, then the theoretical yield of **2a** is 67%.
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