Oxidation

Unusual Reactivity at a Platinum Center Determined by the Ligands and the Solvent Environment**

*Gabriella Tamasi, Renzo Cini, Francesco P. Intini, Maria F. Sivo, and Giovanni Natile**

The oxidation of platinum(II) to platinum(IV) by dihalides (X_2) has been widely investigated in the past years.[1] In this process, two consecutive reactions occur in aqueous solution: 1) Rapid oxidation, assisted by solvent participation, that leads to the formation of a *trans*-haloaquaplatinum(IV) intermediate and a free halide ion, and 2) attack by the halide ion upon the platinum(IV) intermediate to yield the *trans*-dihaloplatinum(IV) end product.[2–4]

The intermediate aqua species formed by this procedure have generally been characterized in solution, but, to the best of our knowledge, they were never isolated as pure solids. We have found that ancillary ligands can stabilize the aqua species to such an extent that it becomes the stable end product. Here we report, for the first time, the X-ray structure of such a species: (*trans*-$[PtCl_3(OH_2)\{N{=}C(OCH_3)CH_2CH_2CH_2\}_2]^+$ (**2**, see Scheme 1). Furthermore, in chlorinated solvents and in the presence of excess chloride, **2** undergoes O-demethylation of the ancillary ligands with release of methyl chloride. The X-raystructure of the demethylation product (*trans*-$[PtCl_3(OH)\{N{=}C(OH)CH_2CH_2CH_2\}\{N{=}C(O)CH_2CH_2CH_2\}]^-$ (**4**, see Scheme 1) is also presented.

The platinum(II) complex *trans*-$[PtCl_2\{N{=}C(OCH_3)CH_2CH_2CH_2\}_2]$ (**1**) reacts with Cl_2 in water to form *trans*-$[PtCl_3(OH_2)\{N{=}C(OCH_3)CH_2CH_2CH_2\}_2]Cl$ (**2**Cl, Scheme 1). This species is stable for days in water in the presence of 5×10^{-2} M HCl and 10^{-3} M **1** (platinum(II) catalyzes the anation reaction, that is, replacement of the coordinated solvent molecule by an entering anion, in platinum(IV) complexes). Other aqua species, under similar reaction conditions, undergo complete anation within minutes.[3] Because of the low solubility of **1** in water, the reaction was repeated by

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[*] Dr. F. P. Intini, Dr. M. F. Sivo, Prof. G. Natile
Dipartimento Farmaco-Chimico
Università degli Studi di Bari
Via E. Orabona 4, 70125 Bari (Italy)
Fax: (+39) 080-544-2230
E-mail: natile@farmchim.uniba.it

Dr. G. Tamasi, Prof. R. Cini
Dipartimento di Scienze e Tecnologie Chimiche e dei Biosistemi
Università degli Studi di Siena
Via A. Moro 2, 53100 Siena (Italy)

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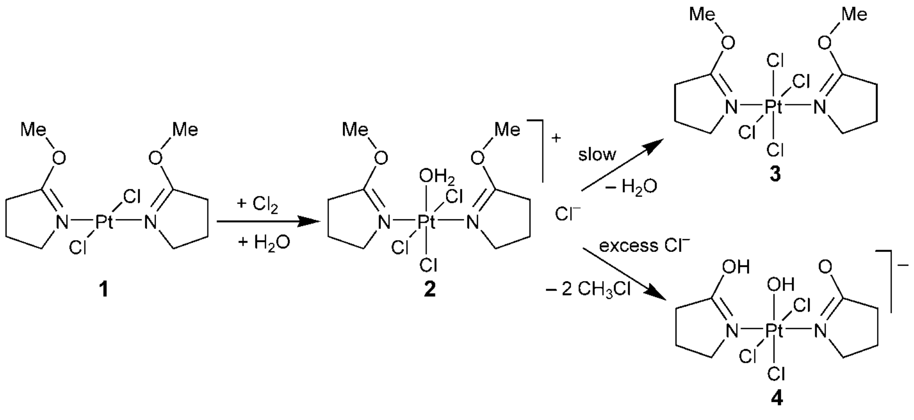

Scheme 1. Synthesis of **2**Cl and further reaction to form **3** or **4**. See text for details.

treating a solution of **1** in chloroform with a solution of Cl_2 in CCl_4 (undried solvents). Again, the only reaction product was the aqua species **2** (see the Supporting Information, Figure S1).

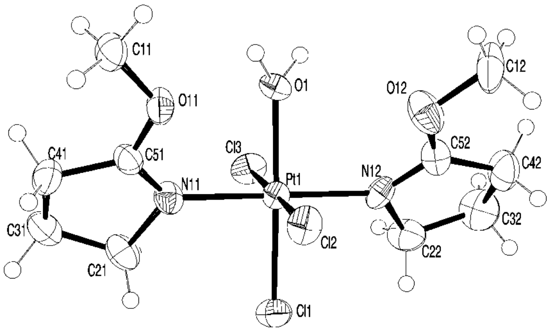

Figure 1. Drawing of complex **2** in the crystalline state. The ellipsoids enclose 50% probability. Selected bond distances [Å] and angles [°]: Pt1–Cl1 2.283(3), Pt1–Cl2 2.308(3), Pt1–Cl3 2.310(3), Pt1–O1 2.035(7), Pt1–N11 2.021(9), Pt1–N12 2.023(9), N11–C51 1.281(15), C51–O11 1.333(14), N12–C52 1.331(15), C52–O12 1.311(15); O1-Pt1-Cl2 94.6(2), O1-Pt1-Cl3 85.1(2), Cl1-Pt1-Cl2 88.8(1), Cl1-Pt1-Cl3 91.5(1), Pt1-N11-C51 129.6(8), Pt1-N12-C52 129.8(8), N11-C51-O11 120(1), N12-C52-O12 118(1).

The X-ray structure of **2** is shown in Figure 1.[5–7] The bond distances agree well with those previously reported for Pt^{IV} complexes (Pt–N 2.022(9), Pt–O 2.035(7), Pt–Cl 2.309(3) Å for mutually *trans* chloride ligands and 2.283(3) Å for chloride *trans* to oxygen).[8] The bond angles between the *cis* ligands are in the range of 88.7–91.5°, except for H_2O-Pt-Cl2 (94.6(2)°) and H_2O-Pt-Cl3 (85.1(2)°). In the organic ligands there is extensive electron delocalization over the oxygen atom and the C=N π system, as already observed in related systems (av C–O 1.32(1), av C–N 1.30(3) Å).[9,10] The methyl groups of the 5-methoxy substituents are directed away from the metal center, thus allowing the methoxy oxygen atoms to be close to the coordinated water molecule (O1···O11 2.68(1), O1···O12 2.87(1) Å).

Under analogous conditions, the related dihydro oxazole complex *trans*-$[\mathrm{PtCl_2}\{\overline{\mathrm{N{=}C(CH_3)OCH_2C}}\mathrm{H_2}\}_2]$ (in which a methyl group has taken the place of the methoxy substituent) reacts with Cl_2 to give the tetrachloro platinum(IV) species *trans*-$[\mathrm{PtCl_4}\{\overline{\mathrm{N{=}C(CH_3)OCH_2C}}\mathrm{H_2}\}_2]$ (see the Supporting Information, Figure S2).[11] Therefore, the presence of two methoxy oxygen atoms is essential for the stabilization of the aqua species **2**.

In chloroform **2**Cl slowly reacts to the tetrachloro species *trans*-$[\mathrm{PtCl_4}\{\overline{\mathrm{N{=}C(OCH_3)CH_2CH_2C}}\mathrm{H_2}\}_2]$ (**3**; $t_{1/2} \approx 12$ h, see Scheme 1 and the Supporting Information, Figure S3). The reaction appears to be catalyzed by a small amount of the platinum(II) compound **1**, which is formed by disproportionation of **2**Cl into **1** and Cl_2.[2] Addition of excess Cl^- does not help in the conversion of **2** into **3**, but instead promotes the demethylation of **2** with formation of *trans*-$[\mathrm{PtCl_3(OH)}\{\overline{\mathrm{N{=}C(OH)CH_2CH_2C}}\mathrm{H_2}\}\{\overline{\mathrm{N{=}C(O)CH_2CH_2C}}\mathrm{H_2}\}]^-$ (**4**) according to Equation (1) (see Scheme 1 and the Supporting Information, Figure S4).

$$\mathbf{2}\,\mathrm{Cl} + (\mathrm{PPh_4})\mathrm{Cl} \rightarrow (\mathrm{PPh_4})\,\mathbf{4} + 2\,\mathrm{CH_3Cl} \qquad (1)$$

Compound **4** is stable in chloroform, even in the presence of excess chloride ion, and represents the first mononuclear platinum complex with 5-hydroxy-3,4-dihydro-2*H*-pyrrole ligands to be isolated and fully characterized. In contrast, a large number of platinum complexes with bridging 5-oxy-3,4-dihydro-2*H*-pyrrole ligands (α-pyrrolidonato) have been reported.[12]

The X-ray structure of **4** is shown in Figure 2. The coordination sphere of **4** is similar to that of **2** (Pt–N 2.050(5), Pt–O 2.025(4), Pt–Cl 2.318(5) Å for mutually *trans* chloride atoms and 2.312(1) Å for chloride *trans* to oxygen; the bond angles between the *cis* ligands are in the range 87.5–91.6°). The Pt–O bond distance is 0.01 Å shorter in **4** than in **2**,

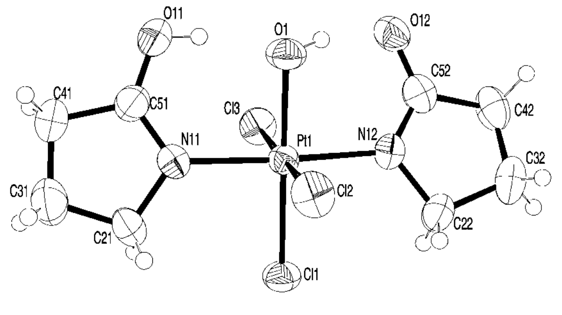

Figure 2. Drawing of complex **4** in the crystalline state. The ellipsoids enclose 50% probability. Selected bond distances [Å] and angles [°]: Pt1–Cl1 2.312(1), Pt1–Cl2 2.313(1), Pt1–Cl3 2.322(1), Pt1–O1 2.025(4), Pt1–N11 2.055(5), Pt1–N12 2.045(4), N11–C51 1.310(7), C51–O11 1.273(7), N12–C52 1.311(7), C52–O12 1.258(7); O1-Pt1-Cl2 87.5(1), O1-Pt1-Cl3 91.1(1), Cl1-Pt1-Cl2 91.1(1), Cl1-Pt1-Cl3 90.4(1), Pt1-N11-C51 124.1(4), Pt1-N12-C52 124.5(4), N11-C51-O11 125.8(5), N12-C52-O12 126.3(5).

while the Pt−Cl distance *trans* to Pt−O is 0.03 Å longer in **4** than in **2**; this reflects the different nature of the O donor (OH^- and OH_2, respectively). The hydroxo ligand, while donating a hydrogen bond to the 5-oxy-dihydropyrrole ligand, accepts a hydrogen bond from the 5-hydroxy-dihydropyrrole ligand (O1···O12 2.551(7) Å, O1-H···O12 165(1)°; O1···O11 2.426(7) Å, O1···H-O11 167(1)°). Furthermore, there is extensive electron delocalization over the oxygen atom and the C=N π system of the dihydropyrrole ligands (av C−O 1.27(1), av C−N 1.31(1) Å).

The demethylation reaction does not take place in the case of compound **3**. Therefore, the coordinated water molecule in **2** appears to play an important role in the nucleophilic substitution of the nearby methoxy group by an external chloride ion. The coordinated water molecule can help in capturing this chloride ion. Furthermore, **2** is positively charged while **3** is neutral, and therefore in chloroform **2** can form an ionic couple with Cl^-. The inertness of **2** in water, even in the presence of 5×10^{-2} M HCl and 10^{-3} M platinum(II) catalyst—as compared to its slow reactivity in chloroform, where it affords **3** or, in the presence of excess Cl^-, **4**—must be connected with the greater ability of water to solvate ionic species.

The O-demethylation is an important reaction in biological systems[13] as well as in organic chemistry.[14] Metal-mediated O-demethylation of coordinated ligands is also described in the literature.[15,16] However, in the case of platinum substrates there are only very few reports. These include Arbuzov-like dealkylation of coordinated phosphites promoted by Cl^-,[17] demethylation of a coordinated O^6-methyldeoxyguanosine with thiophenol,[18] and dealkylation of 2-alkoxyphenylphosphanes to form *O*-metalated chelates.[19] All these reactions generally require high temperatures and long reaction times.

In conclusion, it appears that concepts that usually apply to complex natural substrates—such as intramolecular hydrophobic–hydrophilic interactions and organization of a reactive site—can also apply to simple coordination compounds with interesting and unexpected changes in their behavior. Therefore, compound **2**, in which the coordinated water molecule is surrounded by the oxygen atoms of two 5-methoxy-dihydropyrrole ligands, is favored over the fully chlorinated species **3** and represents the end product in aqueous solution. Moreover, the hydrophilic site of the complex, with a coordinated water molecule and nearby methoxy oxygen atoms, is suited to host the Cl^- anion, which promotes demethylation in a hydrophobic solvent.

Experimental Section

All reagent-grade chemicals were purchased from Aldrich and used without further purification.

Compound **1** was synthesized by ligand cyclization of *trans*-$[PtCl_2\{HN{=}C(OCH_3)CH_2CH_2CH_2Cl\}]$, which was prepared according to the procedure described in reference [9] for analogous compounds. The cyclization reaction was performed in acetone with powdered KOH and is complete in 1 h at 25 °C, leading to the quantitative formation of **1**.

The treatment of **1** in chloroform with a solution of Cl_2 in CCl_4 (undried solvents) leads to the instantaneous and quantitative formation of **2**Cl. A solution of **2** in chloroform, left standing at room temperature, undergoes slow transformation with formation of **3** ($t_{1/2}\approx 12$ h at 25 °C). Treatment of a solution of **2**Cl in chloroform with excess $(PPh_4)Cl$ leads to ligand demethylation with formation of (PPh_4)**4** and release of CH_3Cl ($t_{1/2}\approx 5$ h in 2×10^{-3} M $(PPh_4)Cl$ at 25 °C).

Further details of the synthesis and elemental analysis of **1**–**4** are given in the Supporting Information. The ^1H NMR spectra of **1**–**4** were recorded at 25 °C on a Bruker DMX 300 spectrometer. The spectral changes for the oxidation of **1** to **2**Cl by Cl_2, for the spontaneous transformation of **2**Cl into **3**, and for the reaction of **2**Cl with excess $(PPh_4)Cl$ to give (PPh_4)**4** and CH_3Cl are given in the Supporting Information (Figures S1, S3, and S4, respectively). Because of fast proton exchange between residual water in the solvent and coordinated water molecule (**2**) or hydroxyl groups (**4**), only a broad signal is observed below 2 ppm. This is clearly shown in Figure S3 of the Supporting Information, where the very broad signal at ca. 1.6 ppm in the initial spectrum becomes sharp and shifts to 1.5 ppm as the coordinated water molecule of **2** is replaced by Cl^-.

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[5] Crystal data for **2**Cl·2H$_2$O ($C_{10}H_{24}Cl_4N_2O_5Pt$): $M_w = 589.2$, colorless parallelepiped crystal, monoclinic space group $P21/c$, $a = 16.246(2)$, $b = 7.865(1)$, $c = 15.055(1)$ Å, $\beta = 94.46(1)°$, $V = 1917.8(4)$ Å^3, $Z = 4$, $\rho_{calcd} = 2.041$ g cm^{-3}, Siemens P4 diffractometer, $2\theta_{max} = 50°$, radiation $Mo_{K\alpha}$, $\lambda = 0.71073$ Å, scan mode ω, $T = 293 \pm 2$ K; of 4351 measured reflections, 3350 were independent and 2859 were included in the refinement ($I > 2\sigma(I)$). Lorentz and polarization corrections were performed, absorption corrections were made through the ψ-scan technique, $\mu = 7.893$ mm^{-1}. The structure was solved by direct methods and refined with Fourier methods (SHELX97-WINGX);[6,7] no. of parameters 223, hydrogen atoms were included in calculated positions (HFIX-SHELX97),[6,7] $R1 = 0.0450$ and $wR2 = 0.1494$ for the observed reflections, $R1 = 0.0592$ and $wR2 = 0.1785$ for all reflections, refinement residual electron density 1.813 e Å^{-3}. Crystal data for (PPh_4)**4** ($C_{32}H_{34}Cl_3N_2O_3PPt$): $M_w = 827.06$, pale yellow prism, monoclinic space group $P21/n$, $a = 11.596(2)$, $b = 11.040(2)$, $c = 25.058(5)$ δ Å, $\beta = 99.55(1)°$, $V = 3163.5(10)$ Å^3, $Z = 4$, $\rho_{calcd} = 1.736$ g cm^{-3}, $2\theta_{max} = 50°$, radiation $Mo_{K\alpha}$, $\lambda = 0.71073$ Å, scan mode ω, $T = 293 \pm 2$ K; of 7186 measured reflections, 5574 were independent and 5574 were included in the refinement ($I > 2\sigma(I)$). Lorentz and polarization corrections were performed, absorption corrections were made through the ψ-scan technique, $\mu = 4.776$ mm^{-1}. The structure was solved by direct methods and refined with Fourier methods; no. of parameters 383, $R1 = 0.0323$ and $wR2 = 0.0699$ for the observed reflections, $R1 = 0.0463$ and $wR2 = 0.0749$ for all reflections, refinement residual electron density 0.602 e Å^{-3}. Methods for treatment of hydrogen atoms, instruments, computers and software as for **2**. CCDC-231767 (**2**Cl·2H$_2$O) and CCDC-231768 ((PPh_4)**4**) contain the supplementary crystallographic

data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/conts/retrieving.html (or from the Cambridge Crystallographic Data Centre, 12, Union Road, Cambridge CB21EZ, UK; fax: (+44)1223-336-033; or deposit@ccdc.cam.ac.uk).

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