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A Biomimetic Phenol Substituent Effect on the Reaction of a Dimethylplatinum(II) Complex with Oxygen: Proton Coupled Electron Transfer and Multiple Proton Relay

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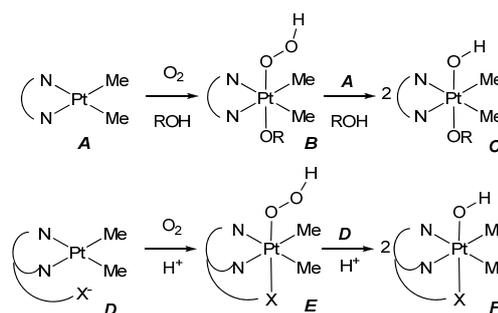
The complex $[\text{PtMe}_2(\{\kappa^2\text{-}N,N\text{-RN=CH-}2\text{-C}_5\text{H}_4\text{N}\})]$ reacts with oxygen in acetone solution to give the platinum(IV) complex $[\text{Pt}(\text{OH})\text{Me}_2\{\kappa^3\text{-}N,N,O\text{-RNH-CH}(2\text{-C}_5\text{H}_4\text{N})(\text{CH=CMeO})\}]$, when $\text{R} = 2\text{-C}_6\text{H}_4\text{OH}$, but not when $\text{R} = \text{Ph}$. It is suggested that the phenol substituent plays two key biomimetic roles; firstly, in proton coupled electron transfer reactions in the activation of oxygen and hydroperoxide groups and, secondly, in proton relay from a methyl group of coordinated acetone.

The use of dioxygen as a selective oxidant in catalysis is highly desirable because oxygen is ubiquitous and the chemistry is inherently green. However, there are major problems to overcome before such selective reactions as the oxidation of alkanes to alcohols can be realised, and so there is intense research activity into oxygen activation with late transition metals.

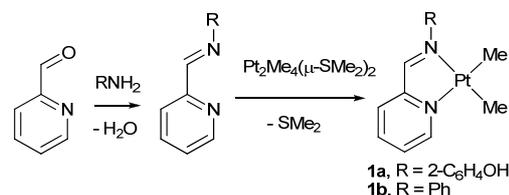
Both metallic platinum and platinum complexes are important in C-H bond activation and in oxidation catalysis, and so the reactivity of organoplatinum complexes with oxygen and oxygen atom donors is a topical field of study. The reaction of dimethylplatinum(II) complexes with oxygen in methanol occurs in two steps, each of which can be considered as a proton coupled 2-electron transfer, first to give a hydroperoxide and then a hydroxide complex (Scheme 1, **A**, **B**, **C**) and the reactivity can be enhanced in the presence of an appended Lewis base (Scheme 1, **D**, **E**, **F**). However, the potential for enhancing reactivity by appending a group containing a proton donor does not appear to have been investigated.

Several enzymes that use oxygen, or which convert hydrogen peroxide to oxygen, have tyrosine residues close to the reaction centre, and the phenol functional group of tyrosine is thought to play a role in proton coupled electron transfer and/or in proton relay to and from the reaction site. To mimic these effects, we have studied the reactions of oxygen with a dimethylplatinum(II) complex which contains a ligand having an appended phenol group.

The ligands $\text{RN=CH-}2\text{-C}_5\text{H}_4\text{N}$, with $\text{R} = 2\text{-C}_6\text{H}_4\text{OH}$ or Ph , were converted to their dimethylplatinum(II) complexes, $[\text{PtMe}_2(\{\kappa^2\text{-}N,N\text{-RN=CH-}2\text{-C}_5\text{H}_4\text{N}\})]$, **1a** and **1b** respectively, as shown in Scheme 2. The complexes were readily characterized by their ^1H NMR spectra. For example, complex **1a** in acetone- d_6 solution gave two equal intensity methylplatinum resonances at $\delta = 0.82$, $^2J(\text{PtH}) = 89$ Hz and 1.21 , $^2J(\text{PtH}) = 87$ Hz, and a singlet imine resonance at $\delta = 9.73$, $^3J(\text{PtH}) = 32$ Hz, the coupling constants being

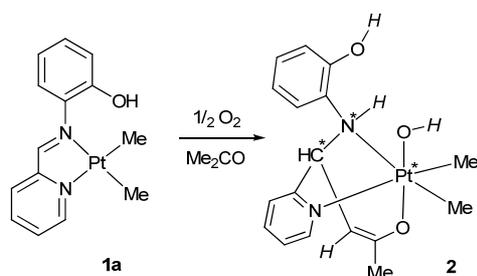


Scheme 1. The reactions of dimethylplatinum(II) complexes with O_2 ($\text{R} = \text{H}, \text{Me}$; $\text{NN} = \text{diimine or diamine ligand}$; $\text{X} = \text{N or O}$)



Scheme 2. The synthesis of dimethylplatinum(II) complexes **1a** and **1b**

characteristic of square planar platinum(II) complexes. The solution of **1b** in acetone- d_6 was stable to air at room temperature, but a solution of **1a** in acetone- d_6 reacted slowly with oxygen to give a new organoplatinum(IV) complex **2-d**, according to Scheme 3. The structure of complex **2** was first determined crystallographically and is shown in Figure 1. The platinum centre has been oxidized to give an octahedral platinum(IV) centre in **2** and an oxygen atom and an acetone molecule have been added to **1a**. However, one methyl substituent of the acetone has been doubly deprotonated, and these protons have been added to the imine nitrogen to form an amine donor and to the oxygen atom to form a hydroxide group (Scheme 3). The resulting MeC(O)=CH group is bound to platinum through the oxygen atom and to the carbon atom of the original imine group of **1a** through the $=\text{CH}$ carbon atom. The addition of acetone to an imine group in organometallic compounds is rare, but there are a few previous examples. Complex **2** contains three chiral centres (Scheme 3, Figure 1) and its formation occurs highly selectively. There are two independent molecules in the asymmetric unit of **2**, and each forms a hydrogen bonded



Scheme 3. The reaction of complex **1a** with oxygen and acetone to give complex **2**. In **2** the phenol proton and protons from the reacted methyl group of acetone are italicized, and the three chiral centres are shown as C*, N* and Pt*.

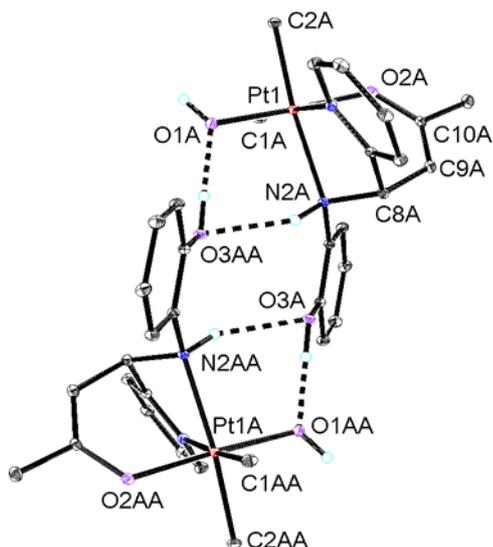


Figure 1. The structure of the H-bonded dimer of complex **2**. Selected distances / Å: O(1A)⋯O(3AA) 2.517(5); N(2A)⋯O(3AA) 2.971(5); Pt(1)-O(1A) 2.011(3); Pt(1)-O(2A) 2.016(3); O(2A)-C(10A) 1.332(6); C(9A)-C(10A) 1.345(6). Symmetry equivalents: x, y, z; 3/2-x, 1/2-y, 1-z.

dimer in which the symmetry equivalent molecules are related by an inversion centre and so have opposite chirality (Figure 1; chirality N(2A)C(8A)Pt(1) is *RSC*; N(2AA)C(8AA)Pt(1A) is *SRA*). The hydrogen atom positions were not directly determined but there are two short contacts for each phenol group (O(1A)⋯O(3AA) 2.517(5); N(2A)⋯O(3AA) 2.971(5) Å), which indicate a strong CO-H-O_{Pt} and a weaker CO⋯H-N hydrogen bond respectively.

The interesting question then remains as to how complex **2** is formed. The reaction was first monitored by ¹H NMR spectroscopy in acetone-*d*₆ solution under ambient atmosphere (Figure 2). Although the reaction is complex, no reaction intermediates were detected, and **2-d**₆ is estimated to be formed in about 90% selectivity over a period of one day. Most significantly, the singlet imine resonance at δ 9.73 for **1a** decayed and was replaced by a new CH resonance at δ 4.79 for **2-d**₆, and the methylplatinum resonances for **2-d**₆ at δ 1.13, and 1.57 each had coupling constants ²J(PtH) = 72 Hz typical

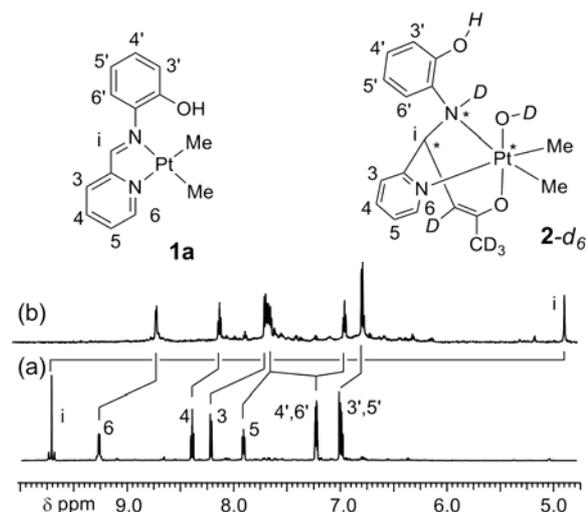
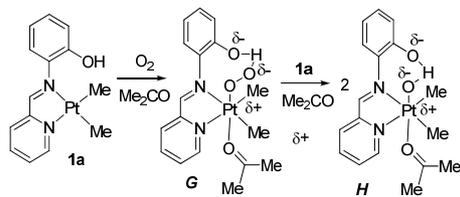


Figure 2. Changes in the ¹H NMR spectrum in the region δ 4.5 – 10 during reaction of **1a** in acetone-*d*₆ with air: (a) spectrum after 5 min. (mostly **1a**); (b) spectrum after 24 h. (mostly **2-d**₆) The positioning of H and D atoms in the OH(D) and NH(D) groups is arbitrary, since they will exchange rapidly.

of platinum(IV) complexes.² In complex **2**, prepared in acetone, the CH-CH= resonances appeared as doublets at 4.77 and 4.17, with ³J(HH) = 9 Hz. The absence of detectable intermediates indicates that the rate determining step is the initial reaction of complex **1a** with oxygen. Consistent with this, the reaction follows second order kinetics, first order in both **1a** and O₂, with *k*₂ *ca.* 0.09 M⁻¹s⁻¹, which is comparable to values of 0.11 and 0.08 M⁻¹s⁻¹ for the oxidation of [PtMe₂(1,10-phenanthroline)] and [PtMe₂(CyN=CH-CH=N-Cy)] in methanol (Scheme 1).²

Based on the above observations, the proton coupled 2-electron transfer steps are proposed to occur according to Scheme 4, in which the phenol unit plays the part of the protic solvent in the reactions of Scheme 1.¹⁻³ Figure 3 shows the calculated structure of the proposed singlet state intermediate **G** and the analogous compound **I** when the phenol group is not present. A strong hydrogen bond is predicted in **G**, and this leads to significant lengthening of the O-O bond compared to **I**, so that complex **G** can be considered to have a hydroperoxide ligand which is hydrogen bonded to the phenoxide group (the calculated OO-H distance is shorter than the CO-H distance, Figure 3).

From the hydroxoplatinum(IV) complex **H** (Scheme 4), a series of proton relay steps is needed to form complex **2**, and a likely sequence is shown in Scheme 5. In the sequence **H**, **J**, **K**, the phenoxide group rotates and abstracts a proton from the coordinated acetone followed immediately by attack of the CH₂⁻ group on the imine carbon. The phenol group rotates to deliver the proton to the amido nitrogen atom, to give **L**. The phenoxide group then rotates back to abstract a proton from the CH₂ group to give **M**, and finally the phenol rotates again to give the observed product **2**. DFT calculations are consistent with this sequence of steps.



Scheme 4. Proposed mechanism of the proton coupled oxidation steps.

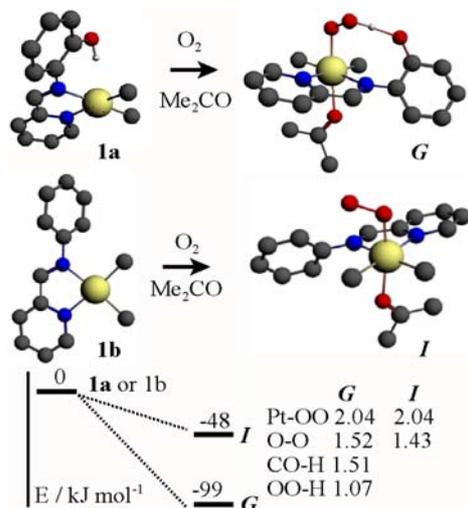


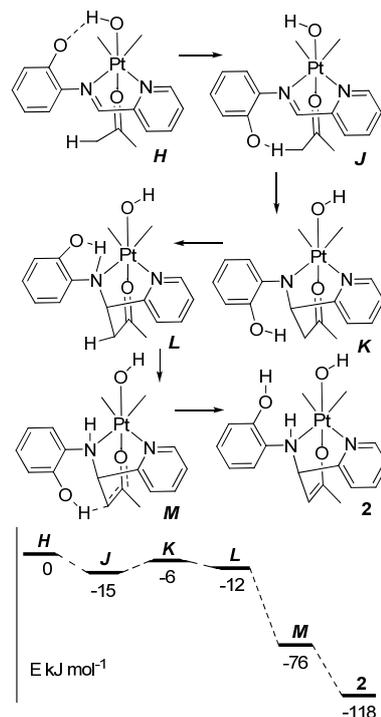
Figure 3. Calculated structures of oxygen/acetone adducts of **1a** and **1b**, and relative energies of **G** and **I**. The singlet is calculated to be lower in energy than the triplet state for both **G** and **I**.

Conclusions

This work shows that the presence of a phenol substituent promotes the reaction of a dimethylplatinum(II) complex **1a** with oxygen, complementing studies which demonstrated a Lewis base effect.² It is suggested that the phenol group plays a vital role in both the proton coupled 2-electron transfer reactions involved in oxidation of platinum(II) to platinum(IV) and then in proton relay steps to give the final product **2** in a highly selective way. The insights gained may be applicable to the design of catalysts for selective oxidation reactions.

Notes and references

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- X-ray data: 2.0.25Me₂CO.0.25H₂O, C_{17.73}H₂₄N₂O_{3.5}Pt, fw 516.48, monoclinic, C2/c, a = 33.626(8), b = 12.052(4), c = 24.064(5), β = 134.007(7), V = 701.5(3), Z = 16, T = 110 K, reflns. total 157762, R1 (all data) 0.0805, wR2 (all data) 0.1112.
- [†] Electronic Supplementary Information (ESI) available: Details of the experimental and theoretical procedures and spectroscopic properties. X-ray data are available in CIF format (CCDC 1058118).
- M.L. Scheuermann and K.I. Goldberg, *Chem. Eur. J.*, 2014, **20**, 14556.
 - V.V. Rostovtsev, L.M. Henling, J.A. Labinger and J.E. Bercaw, *Inorg. Chem.*, 2002, **41**, 3608; E.M. Prokopchuk, H.A. Jenkins and



Scheme 5. A possible mechanism for the proton relay steps in formation of complex **2**, and calculated energies of proposed intermediates

- R.J. Puddephatt, *Organometallics*, 1999, **18**, 2861; A.N. Vedernikov, *Acc. Chem. Res.*, 2012, **45**, 803; W.G. Liu, A.V. Sbergeeva, R.J. Nielsen, W.A. Goddard III and A.N. Vedernikov, *J. Am. Chem. Soc.*, 2014, **136**, 2335; A.V. Sbergeeva, W.G. Liu, R.J. Nielsen, W.A. Goddard III and A.N. Vedernikov, *J. Am. Chem. Soc.*, 2014, **136**, 4761; J.D. Prantner, W. Kaminsky, K.I. Goldberg, *Organometallics*, 2014, **33**, 3227; F. Qu, J.R. Khusnutdinova, N.P. Rath and L.M. Mirica, *Chem. Commun.*, 2014, **50**, 3036.
- O.A. Mironov, S.M. Bischof, M.M. Konnick, B.G. Hashiguchi, V.R. Ziatdinov, W.A. Goddard III, M. Ahlquist and R.A. Periana, *J. Am. Chem. Soc.*, 2013, **135**, 14644; K. Thorshaug, I. Fjeldahl, C. Romming and M. Tilset, *Dalton Trans.*, 2003, 4051; ; K.R. Pellarin, M.S. McCready and R.J. Puddephatt, *Organometallics*, 2012, **31**, 6388; L.A. Wickramasinghe and P.R. Sharp, *J. Am. Chem. Soc.*, 2014, **136**, 13979.
- D.R. Weinberg, C.J. Gagliardi, J.F. Hull, C.F. Murphy, C.A. Kent, B.C. Westlake, A. Paul, D.H. Ess, D.G. McCafferty and T.J. Meyer, *Chem. Rev.*, 2012, **112**, 4016; J.J. Warren, T.A. Tronic and J.M. Mayer, *Chem. Rev.*, 2010, **110**, 6961.
- However, the concept has been applied in other systems. C. Costentin, G. Passard, M. Robert and J.M. Saveant, *J. Am. Chem. Soc.*, 2014, **136**, 11821; T.A. Tronic, W. Kaminsky, M.K. Coggins and J.M. Mayer, *Inorg. Chem.*, 2012, **51**, 10916; R.A. Taylor, D.J. Law, G.J. Sunley, A.J.P. White and G.J.P. Britovsek, *Chem. Commun.*, 2008, 2800.
- J.R. Fetter, J. Qian, J. Shapleigh, J.W. Thomas, A. Garcia-Horsman, E. Schmidt, J. Hosler, G.T. Babcock, R.B. Gennis and S. Ferguson-Miller, *Proc. Natl. Acad. Sci.*, 1995, **92**, 1604; R. Radi, *Acc. Chem. Res.*, 2013, **46**, 550; V. Sharma, K.D. Karlin and M. Wikstrom, *Proc. Natl. Acad. Sci.*, 2013, **110**, 16844; P. Goyal, S. Yang and Q. Cui, *Chem. Sci.*, 2015, **6**, 826.
- J.D. Scott and R.J. Puddephatt, *Organometallics* 1983, **2**, 1643.
- F.J.G. Alonso, V. Riera, M. Vivanco, S.G. Granda and A.G. Rodriguez, *Organometallics* 1994, **13**, 3209; C.M. Anderson, M. Crespo, G. Ferguson, A.J. Lough and R.J. Puddephatt, *Organometallics* 1992, **11**, 1177.