

X-ray Crystal and NMR Structure of a Highly Reactive Bidentate 1,2-Diamine–OsO₄ Complex, Formally a 20-Electron Outer Valence Shell Species. Mechanistic Implications for the 1,2-Diamine-Accelerated Dihydroxylation of Olefins by OsO₄

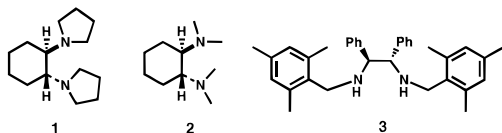
E. J. Corey,* Sepehr Sarshar, Mihai D. Azimioara, Ronald C. Newbold, and Mark C. Noe

Department of Chemistry, Harvard University
Cambridge, Massachusetts, 02138

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The dihydroxylation of olefins by OsO₄ is dramatically accelerated by 1,2-diamines, a phenomenon which underlies the production of chiral 1,2-diols from olefins using various chiral 1,2-diamines.^{1,2} Although the high levels of enantioselectivity which have been observed indicate that the chiral 1,2-diamine may act as a bidentate ligand in the activation of OsO₄, there has been no direct evidence of this point, and even a certain degree of skepticism, since a 1:1 bidentate diamine–OsO₄ complex is, in a formal sense, a 20 outer valence electron structure. We describe herein definitive evidence for just such a structure and provide an analysis of the mechanistic implications.

(*R,R*)-*trans*-1,2-Bis(*N*-pyrrolidino)cyclohexane (**1**) was prepared from (*R,R*)-*trans*-1,2-diaminocyclohexane by reaction in CH₂Cl₂ with 2.2 equiv of 1,4-dibromobutane and 4.4 equiv of triethylamine initially at 0 °C and then at 23 °C for 20 h. Admixture of precooled 0.1 M solutions of OsO₄ and **1** in a ratio of 1:1 at –78 °C in rigorously dry ether and slow cooling from –50 to –80 °C gave deep red crystals, unstable above –40 °C and maintained at –80 °C during isolation, mounting, and X-ray diffraction analysis.



The structure of the 1:1 complex of diamine **1** with OsO₄ is shown in Figure 1.³ Clearly, the diamine **1** functions as a bidentate ligand in the complex with OsO₄. However, the ligand attachments to osmium in the hexacoordinate complex are in an unusual arrangement which is definitely not octahedral. For instance, the angle O(22)–Os–N(1) is 166° and not 180°, and the angle O(22)–Os–O(21) is 106° and not 90°. A simple way to look at the distortion from octahedral geometry becomes evident if one considers the OsO₄ subunit in the complex. That OsO₄ subunit is in between the tetrahedral geometry of uncoordinated OsO₄ and the structure for perfect octahedral

(1) (a) Yamada, T.; Narasaka, K. *Chem. Lett.* **1986**, 131. (b) Tokles, M.; Snyder, J. K. *Tetrahedron Lett.* **1986**, 27, 3951. (c) Tomioka, K.; Nakajima, M.; Koga, K. *J. Am. Chem. Soc.* **1987**, 109, 6213. (d) Hiram, H.; Oishi, T.; Itô, S. *J. Chem. Soc., Chem. Commun.* **1989**, 665. (e) Corey, E. J.; Jardine, P. D.; Virgil, S.; Yuen, P.-W.; Connell, R. D. *J. Am. Chem. Soc.* **1989**, 111, 9243. (f) Tomioka, K.; Nakajima, M.; Koga, K. *Tetrahedron Lett.* **1990**, 31, 6421. (g) Hanessian, S.; Meffre, P.; Girard, M.; Beaudoin, S.; Sancéau, J.-Y.; Bennani, Y. *J. Org. Chem.* **1993**, 58, 1991.

(2) For a review of catalytic asymmetric dihydroxylation of olefins, see: Kolb, H. C.; VanNieuwenhze, M. S.; Sharpless, K. B. *Chem. Rev.* **1994**, 94, 2483.

(3) The deep red orthorhombic crystal of **1**·OsO₄ (0.6 × 0.4 × 0.3 mm) contained four molecules in the unit cell; empirical formula, C₁₄H₂₆N₂O₄·Os (fw 476.57); space group *P*2₁2₁2₁; *a* = 10.987(3), *b* = 11.250(2), *c* = 12.389(2) Å; *V* = 1531.3(6) Å³; *d*(calcd) = 2.067 g/cm³, α = β = γ = 90°; MoKα radiation (0.71073 Å) at 193 K; 2469 reflections collected, with 2001 independent reflections; refinement method full-matrix least squares of *F*²; GOF on *F*², 1.030. Final *R* indices [*I* > 2σ(*I*)], *R*₁ = 0.0444, *wR*₂ = 0.1042; *R* indices (all data), *R*₁ = 0.0534, *wR*₂ = 0.1104; absolute structure parameter 0.04(3). Detailed X-ray crystallographic data are available from the Cambridge Crystallographic Data Center, 12 Union Road, Cambridge, CB2 1EZ, U.K.

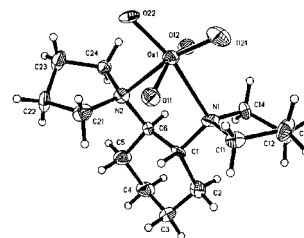


Figure 1. X-ray crystal structure of **1**·OsO₄. Bond lengths (Å): Os(1)–O(22), 1.740(9); Os(1)–O(21), 1.740(12); Os(1)–O(11), 1.756(10); Os(1)–N(1), 2.329(11). Bond angles (deg): O(22)–Os–O(11), 98.9(7); O(11)–Os–O(12), 150.6(5); O(21)–Os–N(1), 88.2(5); O(12)–Os–N(1), 80.1(5); N(1)–Os–N(2), 79.2(4).

geometry. This situation is reminiscent of the observed ligand arrangement about osmium in the 1:1 complex of OsO₄ with quinuclidine.⁴ The pentacoordinate quinuclidine–OsO₄ complex is a distorted trigonal bipyramid in which the OsO₄ subunit geometry lies between the tetrahedral structure of OsO₄ and a regular trigonal bipyramid. The observed structures of **1**·OsO₄ and quinuclidine·OsO₄ can be considered as having a degree of bonding between N and Os which is not strong enough to convert the OsO₄ tetrahedron to a regular octahedron (for **1**·OsO₄) or trigonal bipyramid (for quinuclidine·OsO₄). Griffith, Skapski, *et al.*⁴ have already pointed out that the Os–N bond distance of 2.37 Å observed for quinuclidine·OsO₄ is longer than expected for a single bond and that the structures in the solid and solute are very similar.⁴ It is clear that the two N–Os bonds of **1**·OsO₄ (length 2.33 Å) are also partial bonds, and to this extent it can be argued that the **1**·OsO₄ is something less than a 20 outer valence electron complex. (For example, if the bond order of each of the Os–N bonds were 0.5, then **1**·OsO₄ could be considered as an 18-electron complex.)

¹H and ¹³C NMR studies of 1:1 mixtures of *trans*-1,2-bis(*N*-pyrrolidino)cyclohexane (**1**) or *trans*-1,2-bis(*N*-dimethylamino)cyclohexane (**2**) with OsO₄ indicate a bidentate coordination structure in solution as well as in the solid state. For example, a 1:1 solution of **2** and OsO₄ in CD₂Cl₂–CFCl₃ reveals diastereotopic *N*-Me peaks and other peaks consistent with a C₂ symmetric bidentate structure: ¹H (500 MHz, 200 K) δ 1.02 (2H, m), 1.56 (2H, m), 1.70 (2H, m), 1.93 (2H, m), 2.31 (6H, s), 2.67 (6H, s), 2.77 (2H, m); ¹³C (125 MHz, 200 K) δ 22.84 (CH₂), 24.17 (CH₂), 40.90 (CH₃), 47.74 (CH₃), 64.55 (CH). In addition, these spectra are sharp and invariant (including chemical shifts) over the temperature range 230–183 K, arguing strongly against a rapid equilibrium between two equivalent monodentate complexes.⁵ The ¹H and ¹³C NMR spectra (CD₂Cl₂, 195K) of a 1:1:1 mixture of *trans*-1,2-bis(*N*-pyrrolidino)cyclohexane (**1**), *N*-pyrrolidinocyclohexane, and OsO₄ are an exact superposition of the spectra of a 1:1 mixture of uncomplexed *N*-pyrrolidinocyclohexane and the 1:1 complex of **1** with OsO₄; no free **1** can be detected. Therefore, it follows that the bidentate diamine–OsO₄ complex is much more stable than the monoamine–OsO₄ complex in solution.

trans-1,2-Bis(*N*-pyrrolidino)cyclohexane (**1**) is a much better catalyst for the reaction of osmium tetroxide with olefins than the related monoamine *N*-pyrrolidinocyclohexane. Thus, in CD₂Cl₂ solution at –90 °C the reaction of osmium tetroxide (9 mM) with tetramethylethylene (9 mM) was found by ¹H NMR measurement to be at least 10² faster with *trans*-1,2-bis(*N*-pyrrolidino)cyclohexane than with *N*-pyrrolidinocyclohex-

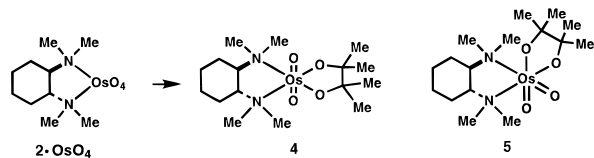
(4) Griffith, W. P.; Skapski, A. C.; Woode, K. A.; Wright, M. J. *Inorg. Chem. Acta* **1978**, 31, L413.

(5) Δ*G*[‡] = <3.5 kcal/mol for an equilibrium between two hypothetical interconverting monodentate complexes is calculated by the method of: Bovey, F. A.; Jelinski, L.; Mirau, P. A. *Nuclear Magnetic Resonance Spectroscopy*, 2nd ed.; Academic Press: New York, 1987; p 300.

ane.⁶ Similarly, a faster rate of reaction (by $> 10^2$) was observed for *trans*-1,2-bis(dimethylamino)cyclohexane (**2**) than for *N,N*-dimethylaminocyclohexane. Given that the bidentate complex of **1** or **2** with OsO₄ is the only one observed in solution and the fact that diamines **1** or **2** are much more potent as accelerators of the reaction of OsO₄ with olefins than are monoamines, it follows that the transition state is bidentate with regard to the diamine.⁷

Diamine **3** is an excellent ligand for the enantioselective dihydroxylation of olefins by OsO₄ at -78 °C, with enantiomeric excess in the region of 95% for a range of olefins from styrene to *trans*-3-hexene.^{1c} These reactions are strongly accelerated by the ligand **3**. For example, *trans*-3-hexene undergoes complete reaction with **3**·OsO₄ at -78 °C in CH₂-Cl₂ within 30 min, as compared to no reaction at all with OsO₄ alone or with the analogous monoamine mesitylmethyl- α -phenylethylamine.^{1c}

¹H NMR studies at low temperature were undertaken to determine the nature of the primary product of the reaction of a 1,2-diamine–OsO₄ complex with an olefin. When a frozen solution of **2**·OsO₄ in CFCl₃–CD₂Cl₂ in an NMR tube at 180 K was overlaid with tetramethylethylene in CFCl₃–CD₂-Cl₂, two frozen layers resulted. The temperature in the NMR instrument was increased gradually until the layers started to melt and mix at 210 K; the spectrum observed was that of **2**·OsO₄ and tetramethylethylene. Within 30 s at 215 K, the formation of the *trans*-dioxo osmate(VI) ester (**4**) resulted, as judged by the new ¹H NMR peaks which coincided with those in the spectrum of authentic **4**.⁸ The thermodynamically less stable *cis*-dioxo osmate ester **5** could not be detected, indicating either that it is not a primary [3 + 2] adduct or that, if it is kinetically preferred, it must isomerize to the more stable *trans*-dioxo osmate ester **4** very rapidly at 215 K. In the event that the *cis*-dioxo osmate ester **5** is a transitory intermediate in the formation of the *trans*-dioxo osmate ester **4**, the observed absolute stereochemical course of the dihydroxylation of olefins by OsO₄ complexed with various C₂ symmetric 1,2-diamines¹ can be explained by the [3 + 2] cycloaddition pathway which was hypothesized earlier.^{1c} However, it is not obvious that such a facile isomerization of **5** to **4** is a reasonable possibility. The most favorable pathway for the conversion **5** → **4** would appear to be one involving dissociation of one of the Os–N bonds, pseudorotation, and Os–N recombination. At least for the case of the *trans*-dioxo osmate ester **4**, Os–N dissociation appears to be a very slow process even at 23 °C, as indicated by the following observations: (1) no ligand exchange of **4** with *N,N,N,N*-tetramethylethylenediamine over 24 h and (2) no decomposition of **4** upon silica gel chromatography. These facts argue that **4** may be the kinetically (as well as thermodynamically) favored product, in which case a direct [3 + 2] cycloaddition pathway predicts the wrong absolute configuration for the osmate ester or 1,2-diol product.^{1c,e} However, an indirect pathway, which correctly predicts absolute configuration, appears deserving of serious consideration.

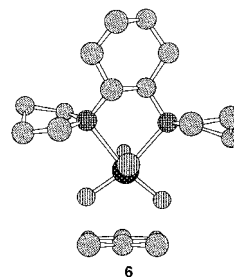


The following hypothesis is advanced for the enantioselective dihydroxylation of olefins by C₂ symmetric 1,2-diamine–OsO₄

(6) The reaction was followed by measuring the decrease in the concentration of tetramethylethylene as a function of time.

(7) Although the faster observed rates of reaction of olefins and OsO₄ with 1,2-diamines as compared with structurally analogous monoamines must be due at least in part to a more favorable equilibrium for 1,2-diamine complexation, our data do not allow an assessment of the degree to which 1,2-diamine rate enhancement may be due to a greater rate constant for the subsequent reaction with olefin.

complexes via attachment of the olefinic carbons to the two equatorial oxygens of the 1,2-diamine–OsO₄ complex. Initial olefin π -coordination to Os occurs in the geometry shown in **6** (for the reaction of **2**·OsO₄–Me₂C=CMe₂) followed by a rapid 90° rotation about the Os–olefin axis to form the *trans*-dioxo osmate adduct **4**. This process is analogous to that proposed for the enantioselective dihydroxylation of olefins by bis-cinchona alkaloid–OsO₄ complexes, except that for the bis-cinchona case the π -complexation step is fast and reversible and the conversion to osmate ester is rate limiting.⁹ This change in rate-limiting step is consistent with the higher electron density on diamine-complexed OsO₄ relative to monoamine-complexed OsO₄. In the diamine–OsO₄ complex the olefin π -complex should be destabilized and the rate of rearrangement to the osmate ester enhanced relative to the monoamine–OsO₄ system.



The dihydroxylation pathway via a rate-limiting π -complexation (as for **6**) and subsequent fast rearrangement to a *trans*-dioxo osmate ester readily explains the observed absolute stereochemistry of dihydroxylation with the most effective diamines such as Tomioka's,^{1c} Jardine's^{1e} (**3**), and Hanessian's.^{1g,10}

It should be noted that the [2 + 2] cycloaddition (osmaoxtane) pathway involving **1**·OsO₄ is inconsistent with the observed absolute stereocourse of the C₂ symmetric 1,2-diamine–OsO₄ reaction¹¹ and with quantum mechanical calculations.¹²

Structure **6**, a distorted cubic octahedral ligand arrangement about Os, is geometrically and sterically feasible for a highly reactive, metastable intermediate or transition state. The symmetry-allowed interaction of electrons in oxygen p-orbitals of the equatorial OsO₂ unit with π^* of the olefin drives the 90° rotation which converts **6** to **4**. Thus, weak π -coordination of the olefin to Os causes sufficient π -electron transfer to the metal so that nucleophilic binding of oxygen to carbon is induced.

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Supporting Information Available: Stereopairs of the osmaoxtane, the π -complex, and the *trans*-dioxo osmate ester from *trans*-stilbene, OsO₄, and the Tomioka diamine (1 page). See any current masthead page for ordering and Internet access instructions.

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(8) NMR spectrum of **4**: ¹H (500 MHz) δ 1.31 (2H, dddd, $J = 2.0, 3.0, 9.4, 11.6$ Hz), 1.51 (2H, dddd, $J = 2.9, 3.0, 3.3, 12.2$ Hz), 1.86 (6H, s), 1.88 (6H, s), 1.97 (2H, dddd, $J = 2.9, 8.2, 9.4, 11.6$ Hz), 2.21 (2H, dddd, $J = 2.0, 8.2, 8.3, 12.2$ Hz), 2.83 (6H, s), 3.29 (6H, s), 3.32 (2H, dd, $J = 3.3, 8.3$ Hz); ¹H (500 MHz, 200 K) δ 1.02 (2H, m), 1.21 (2H, m), 1.53 (2H, m), 1.68 (8H, m), 1.86 (2H, m), 2.77 (4H, m), 3.10 (2H, m), 3.19 (2H, m), 3.51 (2H, m); ¹³C (125 MHz, 200 K) δ 22.93, 25.28, 23.92, 24.20, 49.52, 56.42, 65.65.

(9) Corey, E. J.; Noe, M. C. *J. Am. Chem. Soc.* **1996**, *118*, 319.

(10) A referee has suggested that a transition state involving olefin, OsO₄, and bidentate 1,2-diamine might also be accessed from an intermediate monodentate 1,2-diamine–OsO₄ complex, without specifying structural data for the transition state or the basis for enantioselectivity.

(11) A [2 + 2] cycloaddition pathway for the chiral 1,2-diamine–OsO₄ enantioselective dihydroxylation which would have to involve one of the equatorial oxygens clearly predicts formation of the wrong enantiomer.

(12) A. Veldkamp and G. Frenking (*J. Am. Chem. Soc.* **1994**, *116*, 4937) predict that for diamine-coordinated OsO₄ the osmaoxtane structure "is not a minimum on the potential energy hypersurface."