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A Mechanistic Approach to the Asymmetric Epoxidation of Allylic Alcohols and Osmylation of Alkenes

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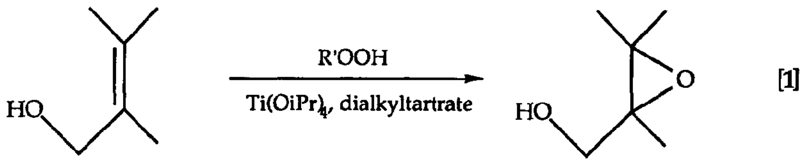
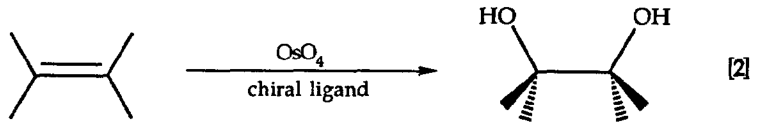
Abstract - A mechanistic study of the oxidation of allylic alcohols to allylic epoxides catalyzed by titanium-tartrate complexes and the *cis*-*dihydroxylation of alkenes by osmium tetraoxide and osmium tetraoxide-chiral diamine ligand complexes is presented. The structure of the titanium-tartrate complexes, and the oxygen transfer in relation to asymmetric epoxidation of allylic alcohols catalyzed by titanium-tartrate complexes are discussed on the basis of the frontier orbital approach; in a similar way is the binding of alkenes to the oxo ligands in osmium tetraoxide and osmium tetraoxide-chiral diamine ligand complexes presented. The results are discussed in relation to the experimental suggested mechanisms.*

The oxidation of alkenes to epoxides and *cis*-1,2-diols are two fundamental reactions in organic chemistry, and in particular are the asymmetric reactions intriguing. Two of these asymmetric reactions are the epoxidation of allylic alcohols catalyzed by titanium-tartrate complexes (the Sharpless epoxidation)[1] (reaction [1]) and the *cis*-dihydroxylation of alkenes catalyzed by osmium tetraoxide-chiral-ligand complexes[2] (reaction [2]).





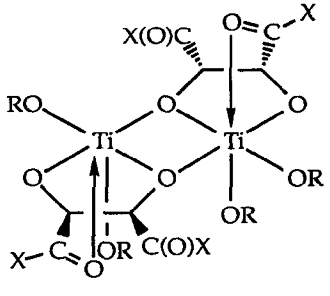
The asymmetric epoxidation of allylic alcohols catalyzed by titanium-tartrate complexes has already found use in the synthesis of organic compounds in which chiral centers are of utmost importance.[3] For the dihydroxylation of alkenes by osmium tetraoxide, the method has demonstrated its advantage in the synthesis of *cis*-1,2-diols,[4] and recently suitable coordinating ligands for osmium tetraoxide for the introduction of enantioselectivity in the osmylation of *trans*-alkenes have been discovered.[2]

One important question in relation to reactions [1] and [2] is: How does the mechanism for the oxygen transfer step lead to the asymmetric induction? Several accounts have been put forward in an attempt to elucidate the mechanism for the asymmetric epoxidation of allylic alcohols catalyzed by titanium-tartrate complexes[2e,g,5] and the dihydroxylation of alkenes by osmium tetraoxide[4,6] and osmium tetraoxide-chiral-ligand complexes.[2a,e,k,7]

The present work is devoted to the mechanism of the asymmetric epoxidation of allylic alcohols catalyzed by titanium-tartrate complexes and the osmylation and enantioselective osmylation of alkenes by osmium tetraoxide and osmium tetraoxide-chiral ligand complexes. For these purposes we have used semi-empirical calculations and the frontier orbital approach.[5a,6a,7] We are aware of the fact that the energy differences between the two optically active stereoisomers are a few kcal·mol^{-1}. The present calculation methods are not reliable at this level. Nevertheless, it is hoped that the mechanistic approaches presented here give substantial clues to the mechanisms of reactions [1] and [2].

I. The mechanism of the asymmetric epoxidation of allylic alcohols catalyzed by titanium-tartrate complexes.

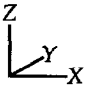
In the discussion of the asymmetric epoxidation of allylic alcohols catalyzed by titanium-tartrate complexes we will address both the structure of the titanium-tartrate complexes and the transfer of an oxygen atom from a coordinated bidentate peroxide group to an alkene, both in a more general way, and in relation to the asymmetric epoxidation of allylic alcohols. Sharpless *et al.* have succeeded in the elucidation of the structures of several titanium-tartrate complexes,[1e] and one of these is shown in **1**:

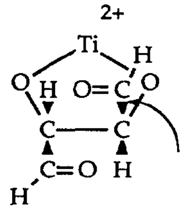


1 R = *i*Pr; X = NHCH$_2$Ph

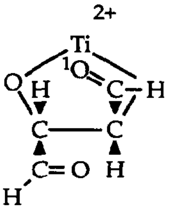
It appears from **1** that each titanium atom is facially coordinated to a tartramide ligand through the two diolate oxygens and one of the carbonyl oxygen atoms. The two isopropoxide ligands are located trans to one of the diolate oxygens and to the carbonyl oxygen. The last titanium coordination site is occupied by a bridging diolate oxygen from the tartramide moiety. This binds the two titanium atoms together, producing pseudooctahedral hexacoordination of both metal centers. It has been suggested that a structure similar to **1** contains structural elements which facilitate the asymmetric catalytic activity.[2e,g] In the following **1** will be used as a model for the active catalyst.

The frontier orbitals of a symmetric model (R,R)-tartrate system, **2**, gives no explanation for the coordination of the bridging diolate from the other tartrate moiety in the *xz* plane; however, the fragment is electron deficient and coordinatively unsaturated. An intramolecular interaction to partially relieve this unsaturation becomes possible. The lowest unoccupied molecular orbital (LUMO) of **2** is of $d_{x^2+y^2}$ symmetry on titanium and points in a direction which favors an interaction with the lone pair electrons located on the oxygen in the carbonyl function. Such an orientation can *e. g.* be achieved by rotation around the C-C bond in **2** (indicated with an arrow), leading to an unsymmetrical titanium-(R,R)-tartrate complex, **3**. The coordination of the carbonyl oxygen to the titanium atom in **3** leads to an overlap between the unoccupied titanium d-orbitals and the lone pair electrons at the carbonyl oxygen. This interaction causes a mixing of the d-orbitals at titanium, and through a mixing of the titanium $d_{x^2+y^2}$, d_{z^2}, d_{xy} and d_{xz} orbitals an asymmetric orbital in the *xz* plane is formed. A contour of this orbital is shown in Figure 1 below.





2



3

Given the asymmetry of this unoccupied orbital depicted in Figure 1 below, an approach of H_2O (a model for the bridging diolate oxygen from the other tartrate moiety) trans to the coordinating oxygen in **3**, leading to **4a**, should be expected to give a more stable titanium-tartrate-water complex. Calculation of the total energy for **4a**, and the corresponding cis analog, **4b**, verify this, the trans complex, **4a**, possessing a total energy 0.47 eV lower than that of the latter. Calculations on more realistic models of different titanium-tartrate dimers lead to the result that the most stable system is the one in which the second titanium-tartrate moiety binds trans to the coordinating carbonyl oxygen, which is in accordance with the simplified model, **4a**, and the X-ray structures of the titanium-tartrate complexes.[1e] It thus appears that by the intramolecular binding of the carbonyl oxygen to the titanium atom an asymmetry is introduced in the titanium-tartrate system.

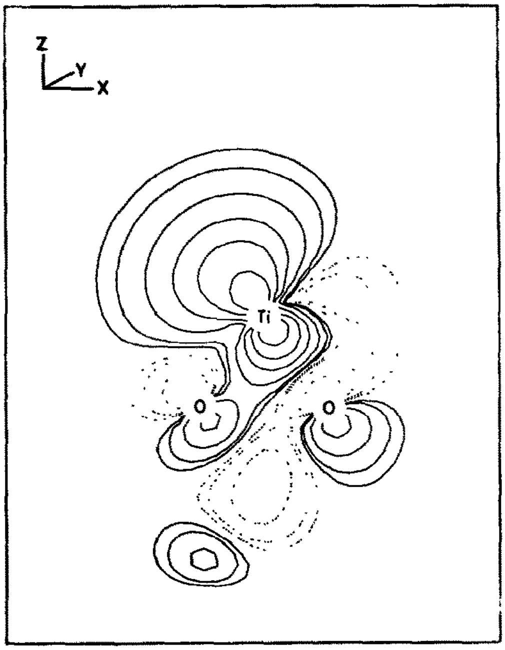
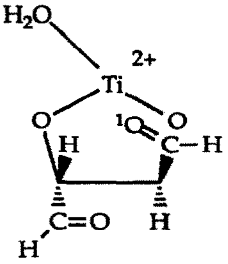
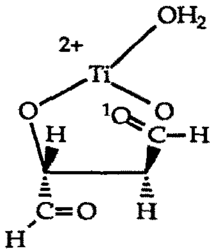


Figure 1. Contour plot of one of the LUMOs of 3.



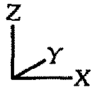
4a

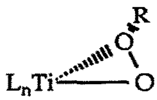


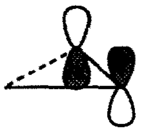
4b

With the internal carbonyl oxygen coordinated to an axial position of the titanium atom and the water molecule (diolate oxygen) equatorially bound to the titanium atom, two vacant sites, one axial and the other equatorial, in **4a** are avaible for coordination. In **1** the isopropoxide ligands are bound to these sites. There is experimental evidence for that a peroxide ligand can bind in a bidentate fashion to a transition metal.[8] In the following it is assumed that the two isopropoxide ligands are replaced by a bidentate alkyl peroxide ligand, from which the oxygen atom is transferred to the alkene. Before proceeding to the titanium-tartrate-peroxide complex, we will briefly discuss the frontier orbitals of a coordinated bidentate peroxide to a titanium atom and how the oxygen transfer can take place from such a bidentate titanium-peroxide complex to an alkene.[9]

The frontier orbitals for a bidentate titanium-peroxide complex, which are of importance for the present study are shown in 5a-c.[9]

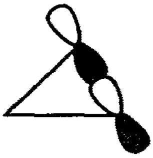






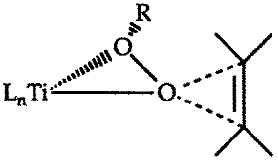
5a

5b

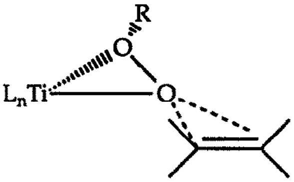


5c

The highest occupied molecular orbital (HOMO) of the titanium-peroxide complex is mainly of p_z character at the peroxygens and antibonding between them, **5a**; right below this HOMO is the second HOMO of p_x character and also antibonding between the peroxygens, **5b**. One of the LUMOs is the $\sigma(O\text{-}O)^*$, **5c** (note that **5c** is shown in the *xy* plane). These three orbitals are set up for interaction with the π orbitals of an alkene, with either the alkene oriented perpendicular, **6a**, or parallel, **6b**, relative to the titanium-peroxide plane, which corresponds to an interaction of the orbitals shown in **5a** or **5b**, respectively, with the alkene π* orbital. The unoccupied MO, **5c**, can interact with the alkene π orbital in both orientations.

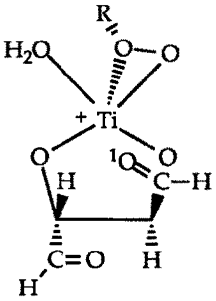


6a

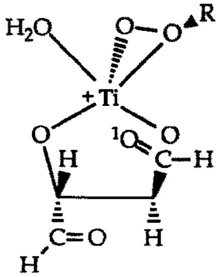


6b

Let us now turn to the titanium-tartrate complex; an alkyl peroxide anion (R-O-O⁻) can coordinate to **4a** in two ways, either with the alkyl group bound to the oxygen which is coordinated in the axial position to titanium, **7a**, or to the oxygen which coordinates to titanium in an equatorial position, **7b**.



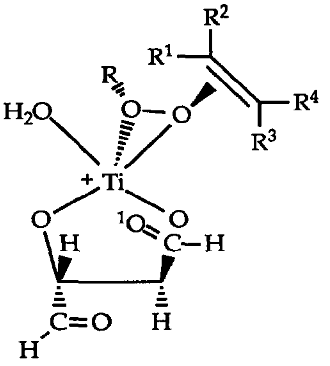
7a



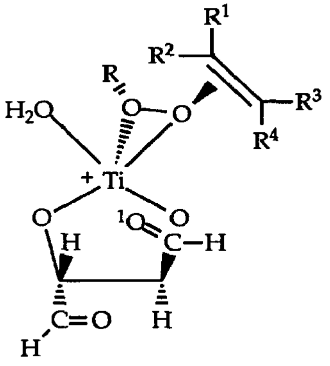
7b

Calculation of the total one-electron energy for the two different binding sites of R (a hydrogen in the actual calculations) to the peroxygen, either to the axial peroxygen (**7a**) or to the equatorial oxygen (**7b**), gives the first as the more stable by 0.43 eV. If one accepts the structure of the titanium-tartrate-peroxide complex as shown in **7a** as the reactive intermediate in these epoxidation reactions, the equatorial peroxygen should thus be expected to be the oxygen which epoxidizes the alkene.

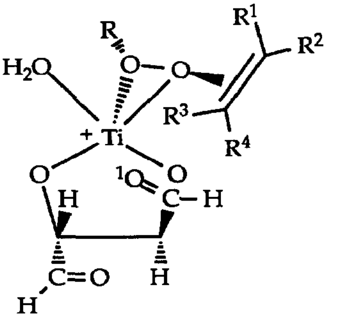
The frontier orbitals of the titanium-peroxide fragment in **7a** are in principle similar to the orbitals shown in **5a-c**. With two orientations of the alkene relative to the titanium-peroxo plane depicted in **6a** and **6b**, there are now in principle four different ways in which an alkene can interact with the equatorial peroxygen in **7a**, because of the two enantio faces of the alkene. It should be noted that we have not taken the allylic alcohol and its binding to titanium into account as this will be considered later. The four different geometric approaches of an alkene to the peroxygen in **7a** are shown below:



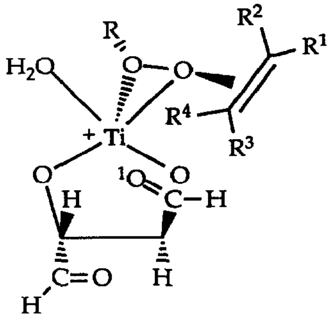
8a



8b

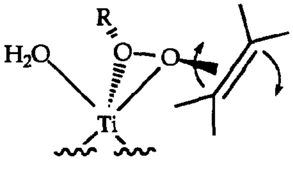


8c



8d

The first step in the analysis of the epoxidation step is devoted to the question if there is a preferred orientation of an alkene at the peroxygen in the titanium-tartrate-peroxide complex. Figure 2 shows the change in energy for the titanium-tartrate-peroxide complex, **9**, as a function of the rotation of the alkene around the equatorial peroxygen.



9

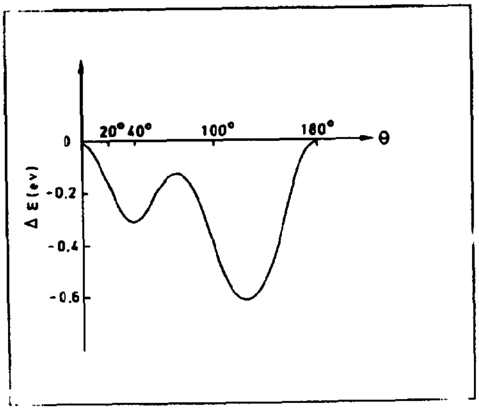
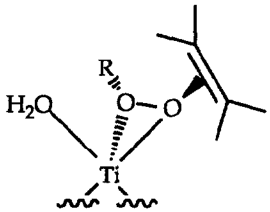
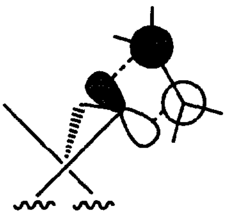


Figure 2. The change in energy for **9** for the rotation of the alkene fragment.

It appears from the energy curve in Figure 2 that the most stable orientation of the alkene relative to the titanium-peroxo plane is one in which the alkene is rotated about 110^0 relative to the equatorial titanium-peroxygen bond. This orientation of the alkene is shown in **10**.



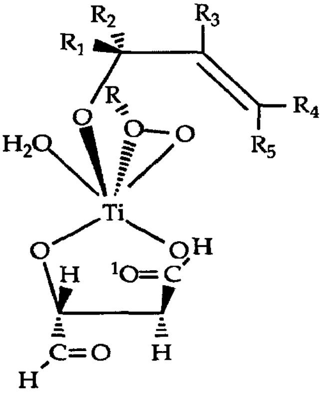
10



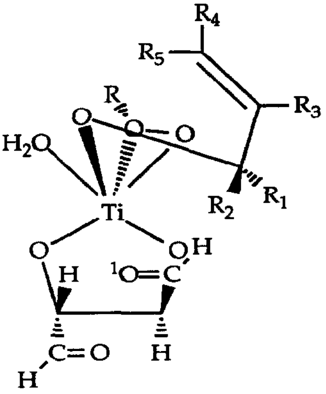
11

The stabilization of the spiro orientation of the alkene relative to the parallel orientation is 0.62 eV. The preferred spiro orientation depicted in **10** can be understood from the frontier orbitals; the lone pair electrons at the equatorial peroxygen, and antisymmetric with respect to the titanium-peroxo plane (**5a**) interact with the π^* orbital of the alkene as shown in **11**. There is an analogous interaction in the parallel geometry, but the two are differentiated by the energy of the lone pair electrons at the peroxygens. The lone pair electrons located at the peroxygen in the titanium-tartrate-peroxide complex perpendicular to the titanium-peroxo plane are located about 0.9 eV higher in energy (and therefore a better donor) than the other lone pair located in the titanium-peroxo plane. Besides this interaction there is also the interaction between the alkene π orbital and one of the LUMOs, the σ(O-O)* orbital, **5c**. The preferred orientation of the alkene is probably due to the presence of the tartrate moiety at titanium.

The preferred spiro orientation of the alkene reduces the four possible geometric approaches of an alkene to the equatorial peroxygen depicted **8a - d**, to two, **8a, b**. With this alignment of the alkene at the equatorial peroxygen, we are now in a position to introduce the allylic alcohol. There are at this stage no vacant coordination sites at titanium, but by making the tartrate fragment symmetric (like 2) by removing the coordination of the carbonyl oxygen (^{1}O) and binding the oxygen of the allylic alcohol to this axial position at titanium leads to the two following transition states, depicted in 12a and 12b, for the epoxidation reaction.

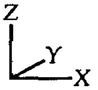


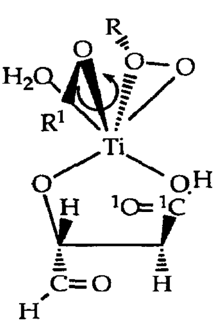
12a



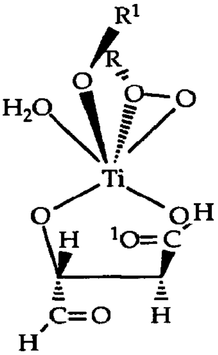
12b

The next step in the study of the asymmetric epoxidation of allylic alcohols catalyzed by titanium-tartrate complexes will address the question whether there is a preferred orientation of the allylic alcohol at the titanium center in an attempt to account for the enantioselectivity of the reaction. Different approaches can be taken for this; in the following we will try to establish that two factors are of importance for the enantioselectivity in this epoxidation reaction; a steric and an electronic. As this study is based on mainly a theoretical approach we will start with the electronic and then on the basis of these results discuss the steric implications. To investigate the electronic factors, we will examine if there is a preferred orientation of an OR^1 (R^1 = H, Me) group bound in the axial position at titanium where the allylic alcohols is bound in 12a, b. The actual model in shown is 13a.





13a



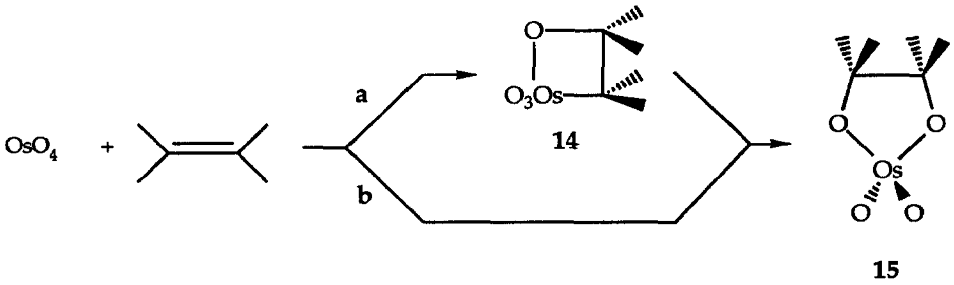
13b

By rotation of the O-R^1 group in **13a** two energy minima are found, one at about 140° and one at about 260° (0° corresponds to the hydrogen or the methyl group oriented in the -z-direction). For R^1 = H the stabilization at these two minima is about 1.1eV, whereas for R^1 = Me a greater stabilization is found, relative to the hydrogen, which is mainly due to steric repulsion between the methyl group and the tartrate fragment, when the methoxy group is oriented towards the tartrate moiety. The stabilization of the O-R^1 group in these two positions appears to be due to an interaction of the lone pair electrons located at the O-R^1 oxygen and an unoccupied orbital at the carbonyl group in the tartrate moiety. The overlap population between the lone pair electrons at the oxygen of the O-R^1 group and the unoccupied orbital at the carbonyl function in the tartrate group (C^1=^{1}O in **13a**) shows maxima at the same dihedral angles as the total energy minima shown, supporting the lone pair - π^* interaction as a reason for the stabilization. The minimum in energy/maximum in overlap population found for a dihedral angle of about 140° corresponds to an orientation of the O-R^1 group as shown in **13b**; this orientation of the O-R^1 group is very similar to the dihedral angle Ti-O-CR^1R^2 in **12a**. The other minimum found at about 260° does not allow an interaction between the alkene part of the allylic alcohol and the equatorial peroxygen. The alkene part of the allylic alcohol in this orientation is located more or less above the bridging diolate oxygen, and no peroxygen is available for transfer. The energy difference between the two orientations of the O-R^1 group in **13a** which corresponds to the two orientations **12a** and **12b**, leading to the two different enantiomers of the allylic alcohol is about 8 kcal·mol^{-1}, favoring the former. It can thus, based on the preferred spiro orientation of the alkene at the equatorial peroxygen relative to the titanium-peroxo plane and the orientation of the O-R^1 group when rotated as outlined in **13a** be concluded that the approach of the allylic alcohol as depicted in **12a** is the most probable. Migration of the equatorial peroxygen to this specific face of the alkene (the peroxygen approaches the alkene part of the allylic alcohol from the bottom) leads to an allylic epoxide with a stereochemistry in accordance with the experimental observations.

The epoxidation step takes place as pointed out earlier by an interaction between the alkene π^* orbital and the lone pair electrons at the peroxygen perpendicular to the titanium-peroxo plane. This interaction is mainly responsible for the spiro orientation of the alkene relative to the titanium-peroxo plane; there is also another interaction of the alkene π orbital with one of the LUMOs in the titanium-tartrate-peroxide complex which is the antibonding titanium d-peroxgen p combination. The alkene can interact with the latter orbital by donation of electron density into it. Allylic alcohols substituted with electron-donating groups at the double bond should favor this interaction, whereas the opposite should be expected for allylic alcohols substituted with electron-withdrawing groups at the double bond. This is in accordance with the experimental results.[2e] The model presented for the asymmetric epoxidation of allylic alcohols catalyzed by titanium-tartrate complexes, **12a**, is consistent with the reactivity pattern (different substituents as R^1-R^5) for the allylic alcohols. The reaction mechanism outlined here is in good agreement with the one suggested by Sharpless *et al.*,[1e,g] but it should be noted that other mechanistic approaches have also been presented.[5b,c]

II. Osmylation and enantioselective osmylation of alkenes by osmium tetraoxide and osmium tetraoxide-chiral ligand complexes.

The dihydroxylation of alkenes by osmium tetraoxide leading to *cis*-1,2-diols will be discussed, first how an alkene binds to the oxygens of osmium tetraoxide, and then how chiral ligands coordinated to osmium tetraoxide might induce the enantioselectivety of this reaction. The transfer of two oxygen atoms from osmium tetraoxide to an alkene is also a part of another problem in oxidation chemistry: Does the oxygen transfer proceed via a metallaoxetane intermediate, **14**, followed by a rearrangement to the osmium(VI) intermediate, **15**, (reaction path **a**) or by direct addition of the alkene to the oxygens (reaction path **b**), giving **15**.[10] The mechanism presented here will be based on a direct addition of the alkene to the oxygens in osmium tetraoxide (path **b**), although a metallaoxetane intermediate cannot be excluded (path a).



The addition of an alkene to osmium tetraoxide will be based on the frontier orbital way of reasoning in terms of an orbital interaction diagram. The frontier orbitals of osmium tetraoxide which are of importance for the present presentation are shown to the left in Figure 3. Osmium tetraoxide has T_d symmetry and the HOMOs are located on the oxygens (the lone pair electrons) and are of p character. Two of these occupied MOs are shown in Figure 3 and are of p_x and p_z character. The LUMOs of osmium tetraoxide are degenerate and are of $d_{x^2+y^2}$ and d_{z^2} character on the metal mixed in with a small part of p_z character on the oxygens as shown in Figure 3. It appears from the shape of the frontier orbitals of osmium tetraoxide that a direct interaction with the frontier orbitals of an alkene is feasible, as the two occupied MOs of osmium tetraoxide and the two unoccupied MOs, shown in Figure 3, are set up for an interaction with the π^* and π orbitals of an alkene, respectively. An interaction diagram for the interaction of osmium tetraoxide with ethylene is shown in Figure 3, where the frontier orbitals of ethylene which are involved in the interaction are shown to the right, and the resulting osmium-ester complex in the center.

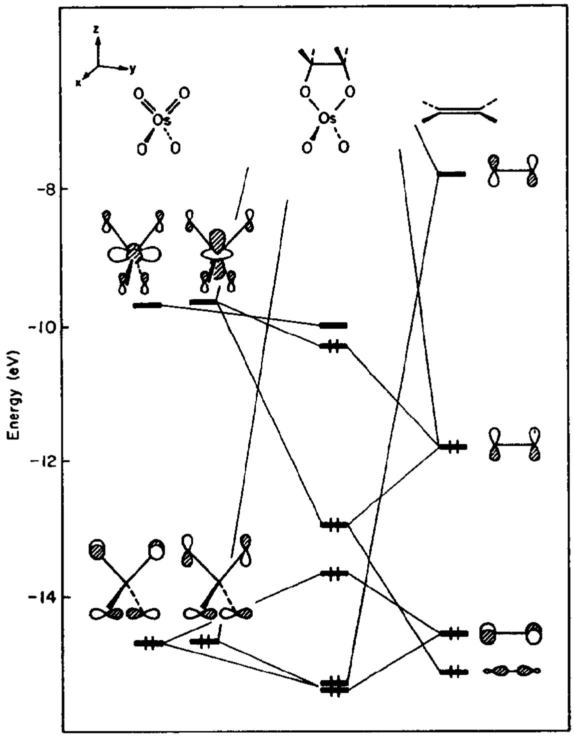
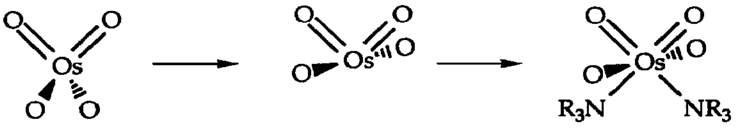


Figure 3. An interaction diagram for a [3 + 2] cycloaddition of osmium tetraoxide and ethylene.

It appears from Figure 3 that the ethylene LUMO π^* orbital interacts with the HOMO of osmium tetraoxide of p_z character on the oxygens. The ethylene HOMO π orbital interacts with the LUMO of osmium tetraoxide of d_{z^2} symmetry, and in this interaction also a lower energy occupied orbital of ethylene is involved. A repulsive interaction between occupied orbitals of the two systems is also observed. It is also seen in the center of Figure 3 that the LUMO of osmium tetraoxide of d_{z^2} symmetry becomes occupied by two electrons by the interaction with ethylene, *i. e.* osmium is reduced from Os(VIII) to Os(VI). In terms of an orbital correlation diagram for the reaction of osmium tetraoxide with ethylene, an appropriate classification is a metal-catalyzed forbidden reaction.[6a]

The presence of tertiary amines in the reaction of osmium tetraoxide with alkenes leads to an increase in the reaction rate,[4] and the presence of some chiral amine ligands leads both to an enantioselective reaction for *trans*-alkenes as well as to an increase in the reaction rate.[2]

It will in the following be assumed that the presence of amine ligands during the reaction causes a geometrical distortion of osmium tetraoxide. Osmium tetraoxide with T_d symmetry can undergo different geometrical distortions; one of these distortions could be to a distortion to osmium tetraoxide with C_{2v} symmetry, **16a**, caused by *cis*-binding of the amines to osmium tetraoxide, **16b**.



16a **16b**

The binding of amines to osmium should be expected to be a favorable interaction since osmium is electron deficient. The binding of amines ase. *g.* pyridine, which is known to increase the rate of osmylation of alkenes, causes also electronic changes of the osmium tetraoxide fragment. Figure 4 shows the change in the frontier orbitals of an osmium tetraoxide-diamine species with C_{2v} symmetry relative to osmium tetraoxide with T_d symmetry.

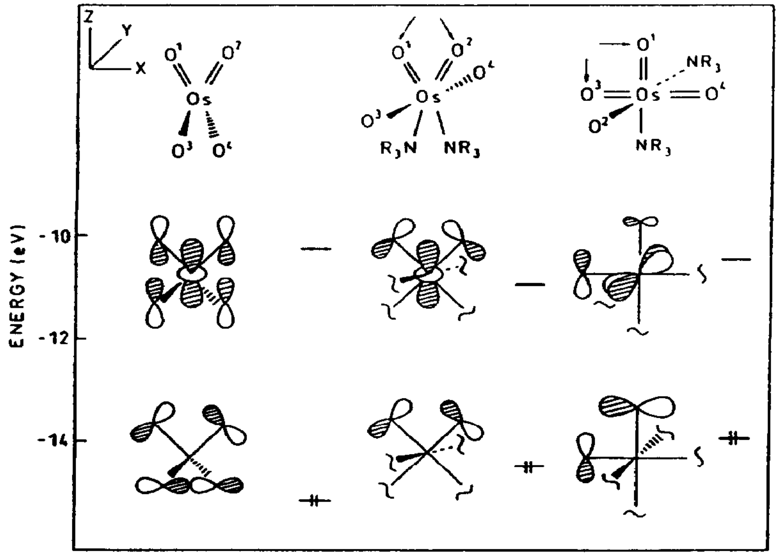
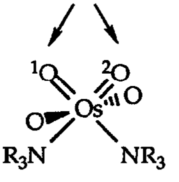


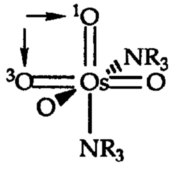
Figure 4. The frontier orbitals of osmium tetraoxide with T_d symmetry (to the left) and an osmium tetraoxide-diamine ligand complex; in the center those of the equatorial oxygens (^1O and ^2O) and to the right those of the equatorial oxygen and the axial oxygen (^1O and ^3O).

It is seen from Figure 4 that the HOMO of osmium tetraoxide, located at the two equatorial oxygens (^1O and ^3O), with the appropriate symmetry for interaction with the alkene π^* orbital is pushed up in energy by the binding of the nitrogen ligands to osmium, whereas the LUMO which has the appropriate symmetry for interaction with the alkene π orbital is pushed down in energy. These changes in energy of the frontier orbitals of the osmium tetraoxide-diamine complex relative to osmium tetraoxide cause the former to become more reactive than the latter as it is both a better electron donor and electron acceptor. The more reactive osmium tetraoxide-diamine complex compared with osmium tetraoxide can also be explained by the energy term from second-order perturbation theory, in which the denominator in principle is the energy difference between the HOMO of the donor and the LUMO of the acceptor. The increase in HOMO energy and the decrease in LUMO energy of the osmium tetraoxide-diamine complex makes the energy difference in the denominator ($\varepsilon_{HOMO-LUMO}$) for the interactions, similar to those depicted in Figure 3, smaller, leading to better interaction, compared with osmium tetraoxide with T_d symmetry. An interaction of the alkene with the two equatorial oxygens in **16b** is in accordance with several X-ray structures of the products formed by reaction of alkenes with osmium-tetraoxide-nitrogene ligand complexes.[11]

Let us now proceed to reactions of alkenes with osmium tetraoxide in the presence of chiral nitrogen ligands; several types of chiral ligands have been used, from cinchona alkaloid ligands[2a-c] to diamines with D_2 or C_2 symmetry.[2d-l] Different mechanistic approaches to the enantioselectivity in the reaction of *trans*-alkenes with osmium tetraoxide-chiral diamine ligands have been presented to account for the stereochemical outcome of the reaction. Both mechanisms taking place *via* a metallaoxetane - a [2+2] cycloaddition[2e] - and a direct interaction of the alkene with the oxygens in the osmium tetraoxide-chiral nitrogen ligand complex - a [3+2] interaction - have been presented.[2k,7] It will in the following be argued for that by changing the interaction of the alkene from the two equatorial oxygens in the osmium tetraoxide-chiral diamine ligand complex, **17a**, to an interaction where one equatorial and one axial oxygen of the osmium tetraoxide-chiral diamine ligand complex are involved, **17b**, leads to an intermediate which accounts for the enantioselectivity in this reaction.

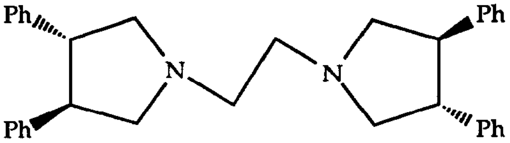


17a



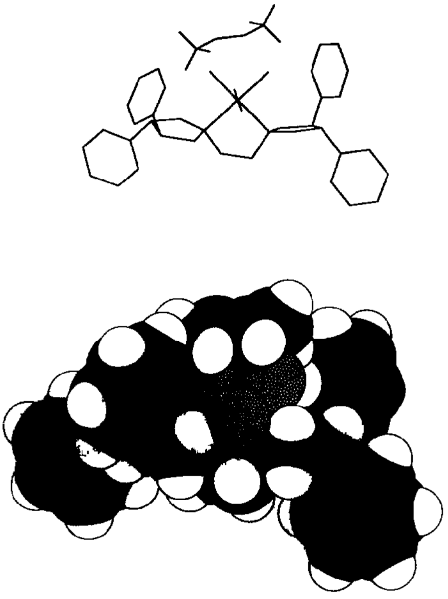
17b

To the right in Figure 4 are shown some of the frontier orbitals located on the equatorial oxygen (^1O) and on the axial oxygen (^3O) of an osmium tetraoxide-diamine ligand complex. The HOMO of the osmium tetraoxide-diamine ligand complex, **17a**, (in the center of Figure 4) is raised by 0.37 eV, whereas the LUMO is lowered by 0.78 eV relative to osmium tetraoxide with T_d symmetry (shown to the left in Figure 4). The HOMO and LUMO located on the equatorial oxygen (^1O) and the axial (^3O), **17b**, shown to the right in Figure 4, which have the appropriate symmetry to interact with an alkene are raised 0.62 eV and lowered 0.41 eV in energy, respectively, relative to osmium tetraoxide with T_d symmetry. The geometrical distortion of osmium tetraoxide from T_d symmetry to C_{2v} symmetry by the binding of the amine ligands causes also changes in the osmium-oxo overlap population (a measure for the bond strength). In osmium tetraoxide with T_d symmetry the osmium-oxo overlap population is 0.845, whereas it is reduced to 0.712 for the Os-^{1}O bond, and to 0.724 for the Os-^{3}O bond in **17b**. These reductions in overlap populations, which also are found in **17a**, might also help to account for the increased reactivity of osmium tetraoxide in the presence of nitrogen ligands. The amplitudes of the HOMO and LUMO in **17a** and **17b** are also affected by the geometrical distortion relative to osmium tetraoxide with T_d symmetry; the two equatorial oxygens in **17a** have amplitudes for the unoccupied and occupied MO of 0.31 and 0.52, respecticely. The numbers for the equatorial oxygen (^{1}O) and the axial oxygen (^{3}O) in **17b** are: 0.20 and 0.31 for the unoccupied MO and 0.58 and 0.43 for the occupied MO. These numbers indicate that the equatorial oxygen in the osmium tetraoxide-diamine ligand complex is more nucleophilic than the axial oxygen, whereas the axial oxygen is more electrophilic than the equatorial oxygen. It appears thus, from an electronic point of view, that there are two addition modes of an alkene to the osmium tetraoxide-diamine ligand complex. The two different approaches of an alkene depicted in **17a** and **17b**, have been tested in the reaction of *trans*-alkenes with osmium tetraoxide in the presence of a chiral diamine. The following modelling results have been performed with the chiral diamine **18**.

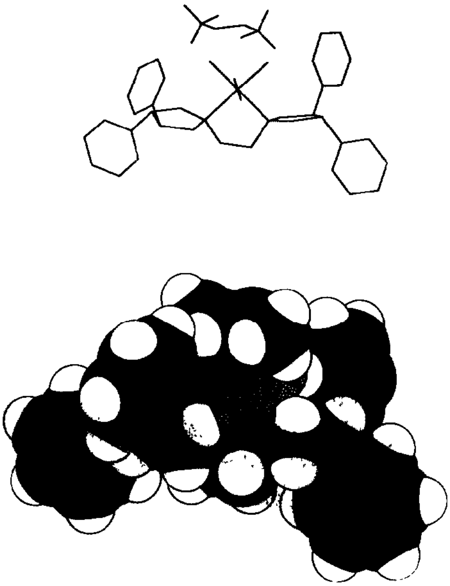


18

A model for the two addition modes of *trans*-2-butene (the simplest model for a *trans*-alkene) to the two equatorial oxygens in an osmium tetraoxide-**18** complex is shown in **19a** and **19b**. In the upper models the hydrogen atoms are shown in the two methyl groups of *trans*-2-butene, but omitted in the rest for clarity. The osmium tetraoxide-**18** model is based on the X-ray structure of similar type of systems and on MM2 calculations in which the octahedral core around the osmium atom was kept fixed.



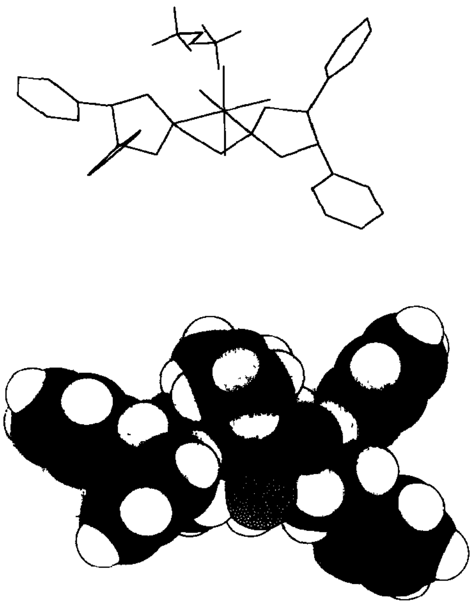
19a



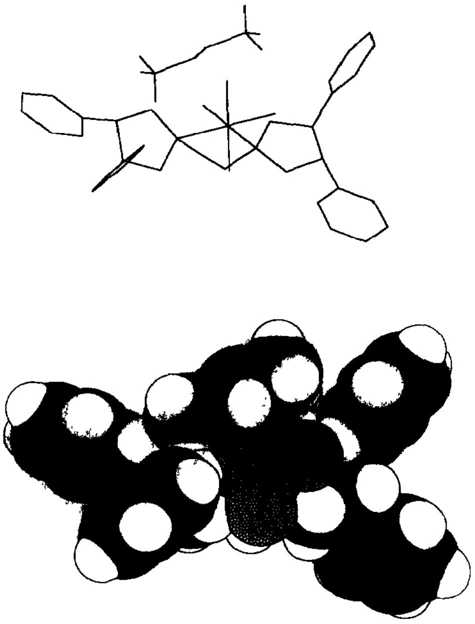
19b

The approach of the alkene in **19a** leads to dihydroxylation of the (S,S) face of the prochiral alkene, whereas the approach of the alkene outlined in **19b** causes dihydroxylation of the (R,R) face. The carbon-oxygen distances were chosen as 1.9 Å. It appears from the space-fillings models depicted as the lower part of **19a** and **19b**, that the dihydroxylation of the (S,S) face is unfavorable because of steric repulsion between the methyl groups in the alkene and the phenyl groups in the osmium tetraoxide-**18** complex, whereas the (R,R) face is sterically more favorable.

Changing the interaction of the alkene from the two equatorial oxygens in the osmium tetraoxide-**18** complex, as shown in **19a** and **19b**, to an interaction where one equatorial oxygen and one axial oxygen are involved leads to the two models depicted in **20a** and **20b**. The approach of the alkene shown in **20a** causes dihydroxylation of the (R,R) face of the alkene, whereas **20b** leads to dihydroxylation of the (S,S) face. The steric repulsion picture between the substituents in the *trans*-alkene in **20a, b** is reversed compared with the repulsion found for the approaches in **19a** and **b**.



20a



20b

Osmylation of *trans*-alkenes in the presence of chiral ligands as 18[2d-f] and ligands of similar type[2h-l] gives a stereochemistry of the diols formed which are not easily justifiedr by "the normal addition" modes of the alkene to osmium tetraoxide-chiral diamine complex, in which the addition takes place to the two equatorial oxygens. However, the alternative approach in which the alkene adds to one equatorial and one axial oxygen in the osmium tetraoxide-chiral diamine complex, **20a**, seems to agree with the experimental results. The approach of *trans*-alkenes to the oxygens on the osmium tetraoxide-chiral diamine complex as outlined in **20a** is in contrast to a mechanism proposed for this particular reaction where a metallaoxetane was invoked in the crucial step by Tomioka *et al.*,[2e] whereas is supports the idea put forward by Corey *et al.*[2k]

Calculation details.

The calculations were performed using semi-empirical calculations, either using the extended Hückel or the INDO method.[5a,6a,7] The structures for the involved species were taken from the crystal structures,[2e] or adjusted to be very similar to known structures. The bond length for the titanium-oxygen (H_2O) bond has been chosen as 2.16 Å, which is similar to the bond length between titanium and the bridging diolate oxygen. The structure of the titanium-tartrate peroxo complex has been adjusted so it fits the peroxo part of a similar complex.[8] For the osmium systems the data were taken from ref. 11.

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