to predict the chirality *S* for the created hydroxylic center. In such a case the observed *S* chirality of the chromancarboxaldehyde **1b** would support a syn $S_{N'}2$ mechanism for the stereospecific cyclization of molecule **8b**.

Further applications of this methodology to the asymmetric synthesis of other natural products are in progress.

Acknowledgment. Financial support from Rhône-Poulenc S.A. is gratefully acknowledged.

Registry No. 1b, 69400-39-1; **1b**, 91712-49-1; **3**, 91796-57-5; **4**, 61187-71-1; (*Z*)-**5**, 91712-50-4; (*E*)-**5**, 91712-51-5; **6**, 91712-52-6; **7**, 91712-53-7; **8a**, 91712-54-8; **8b**, 91741-62-7; **9**, 91712-55-9; pyruvic aldehyde dimethyl ketal, 6342-56-9.

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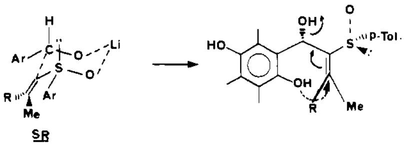
[17] See reaction below:



On the Mechanism of Metal-Catalyzed Epoxidation: A Model for the Bonding in Peroxo-Metal Complexes

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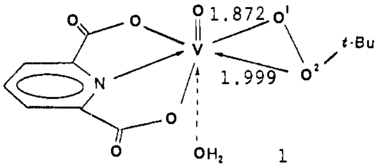
The transfer of oxygen from alkyl hydroperoxides may be effectively catalyzed by high-valent d^0 transition-metal complexes (e.g., Mo^{VI}, V^V, Ti^{IV}). This epoxidation reaction is used extensively in the commercial production of propylene oxide[1] and in many aspects of organic synthesis.[2,3] Although controversy still surrounds the mechanism of these reactions,[4] considerable insight into the subtleties of this catalytic process has resulted from a variety of physical organic data.[3] The X-ray crystal structure of (dipic)VO(OO-*t*-Bu)H_2O (**1**) is a deformed pentagonal bipyramide with the peroxo oxygens in the equatorial plane.[5] The most striking aspect of this complex is that the proximal oxygen-metal bond is only slightly longer than that of the coordinated distal oxygen-metal bond. While hydrogen peroxide is not sufficiently reactive to epoxidize a nonconjugated carbon-carbon double bond, its "electrophilicity" may be markedly enhanced by placing it in conjugation with a multiple bond (e.g., C=O, C=NH).[6] The alkaline-earth anions of H_2O_2 or ROOH will epoxidize conjugated alkenes by a mechanism involving a Michael-type addition.[7] We attribute the fact that ROO^- does not react with simple alkenes to the "super nucelophilicity" of this anion as a consequence of the α-effect.[8] How then can d^0 metal complexes of ROO^- exhibit "electrophilic" behavior toward simple alkenes? We now provide a general theoretical model that describes the metal-peroxide bonding in such complexes and an explanation for why these metal-bound "peroxy anions" can readily transfer oxygen to nucleophilic alkenes.



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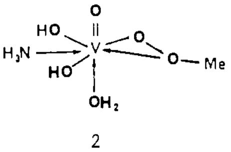

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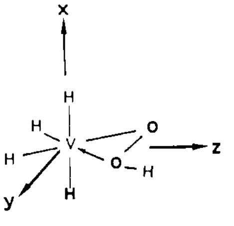

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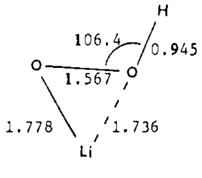

4

It is instructive to first examine the frontier MOs (FMO) of the anti periplanar conformer of H_2O_2. The HOMO (ψ_9) lies in the plane of the four atoms and is comprised of a combination of a σ O-O bond and an orbital of "π^* symmetry". The LUMO (ψ_{10}) is the σ^*_{O-O} with a contribution from an in-plane orbital of π-symmetry (Figure 1).[9] It is a σ O-O bond that must be broken during an oxygen transfer from a peroxo complex. Employing LiOOH (**4**) as a model that can be adequately treated theoretically with ab initio calculations,[10] we found that a bridged structure existed at an energy minimum.[11] The HOMO of LiOOH is the π^*_{O-O} orbital ($\psi_{10'}$) that is orthogonal to the molecular plane. The in-plane orbitals, which are involved in the oxygen transfer, give rise to three MOs that are reminiscent of the Walsh orbitals of ethylene oxide.[12a] The next HOMO

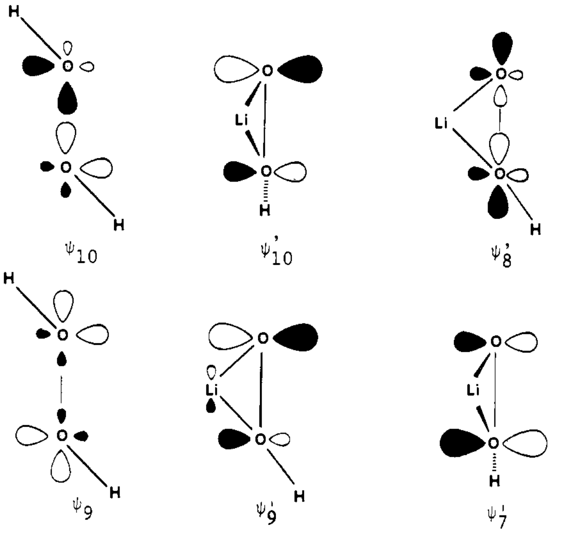

Figure 1. Frontier molecular orbitals of H_2O_2 and LiOOH (STO-3G).

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[1] (a) Landau, R.; Sullivan, G. A.; Brown, D. *ChemTech* **1979**, 602. (b) Shell Oil, Brit. Pat. 1 249 079, 1971. Shell Oil, U. S. Pat. 3 923 843, 1975.

[2] (a) Sharpless, K. B.; Verhoeven, T. R. *Aldrichimica Acta* **1979**, *12*, 63. Behrens, C. H.; Sharpless, K. B. *Ibid.*, **1983**, *16*, 67. (b) Sharpless, K. B.; Behrens, C. H.; Katsuki, T.; Lee, A. W. M.; Martin, V. S.; Takatani, M.; Walker, F. J.; Woodard, S. S.; Viti, S. M. *Pure Appl. Chem.* **1983**, *55*, 589.

[3] Sharpless, K. B.; Woodard, S. S.; Finn, M. G. *Pure Appl. Chem.* **1983**, *55*, 1823.

[4] For an alternate viewpoint of the mechanism involving a peroxometallocyclic intermediate, see: (a) Mimoun, H. *J. Mol. Catal.* **1980**, *7*, 1. (b) Chaumette, P.; Mimoun, H.; Saussine, L.; Fischer, J.; Mitschler, A. *J. Organomet. Chem.* **1983**, *250*, 291.

[5] Mimoun, H.; Chaumette, P.; Mignard, M.; Saussine, L. *Nouv. J. Chim.* **1983**, *7*, 467.

[6] For a discussion with previous references, see: Arias, L. A.; Adkins, S.; Nagel, C. J.; Bach, R. D. *J. Org. Chem.* **1983**, *48*, 888.

[7] Apeloig, Y.; Karni, M.; Rapport, Z. *J. Am. Chem. Soc.* **1983**, *105*, 2784.

[8] Hoz, S. *J. Org. Chem.* **1982**, *47*, 3545.

[9] The lower lying occupied π (ψ_7) and π^* (ψ_8) orbitals of the O-O bond are orthogonal to the molecular plane of the H_2O_2 molecule.

[10] The calculations were performed with the GAUSSIAN 80 series of programs with standard MO theory. Both minimal STO-3G and split valence 4-31G basis sets were used: Binkley, J. F.; Whiteside, R. A.; Krishnan, R.; Seeger, R.; DeFrees, D. J.; Schlegel, H. B.; Topiol, S.; Kahn, L. R.; Pople, J. A. *QCPE* **1981**, *13*, 406.

[11] The structure of LiOOH is basis set dependent since the molecule is essentially linear (O-O-Li = 176°) with an STO-3G basis set. Minimizing the geometry by 4-31G, with the OOLi bond angle constrained to the STO-3G minimum of 176°, results in an increase in energy of 18.8 kcal/mol relative to the cyclic 4-31G minimized structure.

[12] (a) Bach, R. D.; Wolber, J. G. *J. Am. Chem. Soc.* **1984**, *106*, 1401. (b) Bach, R. D.; Wolber, J. G. *J. Am. Chem. Soc.* **1984**, *106*, 1410.

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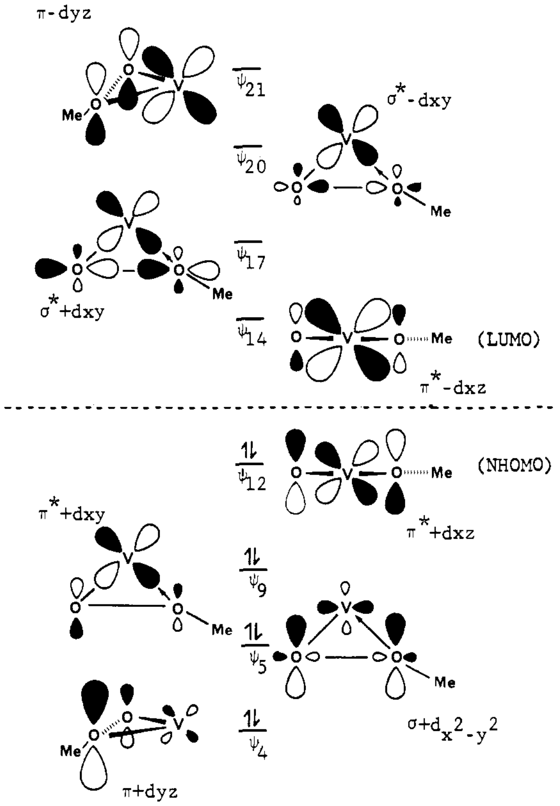

Figure 2. Frontier molecular d orbitals for vanadium complex **2**.

(NHOMO) has π^* symmetry and exemplifies how a metal, using an empty diffuse p orbital, has the proper symmetry to migrate from the distal oxygen (O2) to the "metal-bearing" oxygen. The next two lower lying occupied MOs of LiOOH constitute the $\sigma_{\text{O-O}}$ ($\psi_{8'}$) and the $\pi_{\text{O-O}}$ ($\psi_{7'}$) orbitals.

We have superimposed a set of d orbitals on the metal center and defined their role in epoxidation. The successful utilization of a vanadium cation with low-energy empty d orbitals (d^0) becomes immediately evident upon examination of the FMOs for complex **2** (Figure 2).[13] Since the ground-state π and π^* orbitals of an O–O bond are both occupied, a unique opporunity exists for d orbital participation. The NHOMO (ψ_{12}) and ψ_4 in **2** represent dπ–pπ bonding MOs of the d_{xz} and d_{yz} orbitals with the π^* and π O–O bonds, respectively. The LUMO (ψ_{14}) and ψ_{21} are the antibonding (empty) combinations of these MOs. The occupied in-plane orbitals that are responsible for the "σ-type" bonding in this complex utilize the d_{xy} (ψ_9) and $d_{x^2-y^2}$ (ψ_5) orbitals. These metal d orbitals are ideally situated to facilitate a symmetry allowed 1,2 migration of the metal across the O–O bond in both the σ and π planes.

The principal axis of reaction in alkene epoxidation involves a "backside" attack by the alkene π-bond on both the σ (ψ_5) and σ^* (ψ_{17}) orbitals of the O–O bond. The electrophilic nature of the peroxo moiety is attributable to the steep descent in energy of the σ^* O–O orbital resulting from the perturbation of the σ O–O bond mediated by its molecular collision with the alkene. The net effect of this stabilizing, four-electron three-MO electronic interaction is to lower the enthalpy of activation for oxygen transfer to the alkene.[12b]

In summary, successful metal catalysts possess low-lying empty d orbitals that can facilitate an oxygen transfer with a simultaneous 1,2 metal migration without disruption of metal–oxygen bonding. The metal atom in bridged species like **1** provides a source of "internal solvation" that reduces the amount of desolvation that this nucleophilic oxy anion would require relative to a simple hydroperoxy anion. For example, the gas-phase activation barrier for transferring oxygen from HOO^- to ethylene (+38.9 kcal/mol, STO-3G) is lower than that for LiOOH (+43.6 kcal/mol, spiro geometry).[12b,14] The order in reactivity would be reversed in solution due to solvation that lowers the energy of a "naked" anion.

Finally, we conclude that the bonding of a filled in-plane orbital with "π^*-type" symmetry on the peroxide with an empty d orbital on the metal (ψ_9) is the single most important bonding characteristic of these bridged peroxo epoxidizing agents. The direction of electron flow is the antithesis of that of the Dewar–Chatt model[15] for the π-complexation of alkenes with metals, where electron density flows from a filled metal d oribtal to the empty π^* oribtal of an alkene.

Acknowledgment. We are grateful to Wayne State University Computing Center for generous amounts of computational time and to Professors H. Bernhard Schlegel and K. Barry Sharpless for their helpful discussions.

Registry No. 2, 91842-63-6; **3**, 91842-64-7; LiOOH, 23594-83-4; H_2O_2, 7722-84-1.

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[13] The bonding characteristics in vanadium complex **2** were examined by using extended Hückel calculations where ab initio (STO-3G) methods were employed on **3**. Both methods afforded d orbitals of remarkable similarity. The d orbitals shown are those of complex **2**. The calculated relative energies of these MOs were also the same with the exception of one reversed order in the higher lying empty orbitals. The basis set for vanadium was taken from: Tatewaka, H.; Huzinaga, S. *J. Chem. Phys.* **1979** *71*, 4339.

[14] The calculated barriers (4-31G) for oxygen transfer from LiOOH to ethylene are 22.8 and 23.6 kcal/mol for a spiro and a planar orientation of reactants.

[15] (a) Dewar, M. J. S. *Bull. Soc. Chim. Fr.* **1951**, *18*, C79. (b) Chatt, J.; Duncanson, L. A. *J. Chem. Soc.* **1953**, 2939.

(±)-Linaresine and (±)-Dihydrolinaresine. The Possible Conversion of Protoberberinium Salts into Cularine Alkaloids

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Polycarpine (**3**) is an unusual amide first obtained from a member of the Annonaceae.[1] In 1979, it was recognized that the biogenesis of this pseudobenzylisoquinoline alkaloid probably proceeds from the known protoberberinium salt palmatine (**1**). Indeed, in vitro oxidation of **1** with *m*-chloroperbenzoic acid was found to afford polycarpine (**3**), and similar oxidation of the common protoberberinium salt berberine (**2**) led to the hitherto unknown polyberbine (**4**).[2]

As a result of a detailed investigation of the alkaloids of *B. valdiviana* Phil. (Berberidaceae),[3] we have now obtained amorphous polyberbine (**4**), $C_{20}H_{19}NO_6$, for the first time from a natural source, where it is accompanied by berberine (**2**).[4]

But the more significant finding was in our subsequent isolation from the same source of the two novel, colorless, and alcoholic alkaloids (±)-linaresine (**9**) and (±)-dihydrolinaresine (**8**), both

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[1] Jossang, A.; Leboeuf, M.; Cavé, A.; Damak, M.; Riche, C. *C. R. Hebd. Seances Acad. Sci., Ser. C* **1977**, *284*, 467.

[2] Murugesan, N.; Shamma, M. *Tetrahedron Lett.* **1979**, 4521.

[3] Guinaudeau, H.; Elango, V.; Shamma, M.; Fajardo, V. *Chem. Commun.* **1982**, 1122.

[4] A total of 20 kg of *B. valdiviana* gave 25 mg of polyberbine (**4**): $\lambda_{\max}$ MeOH 216, 332 nm (log ϵ 4.51, 4.17); $\nu_{\max}$ $CHCl_3$ 1610, 1660, 3500 cm^{-1}; MS, *m/z* 369 (M^+, 100), 352 (33), 341 (34), 326 (39), 324 (37), 308 (57), 294 (23). Ethereal diazomethane O-methylation of **4** furnished *O*-methylpolyberbine, identical with semisynthetic material.[2]