Site Specificity in the Photooxidation of Some Trisubstituted Alkenes in Thionin-Supported Zeolite Na−Y. On the Role of the Alkali Metal Cation
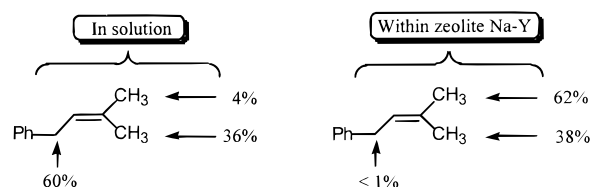
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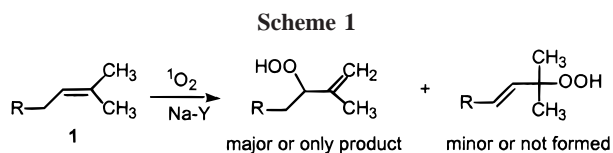
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ABSTRACT

The less substituted side of some geminal dimethyl trisubstituted alkenes becomes significantly more reactive if photooxygenation takes place in thionin-supported zeolite Na−Y. These results are mainly attributed to a synergistic interaction between the alkali metal cation, the alkene, and the oxygen in the transition state of perepoxide formation.

The photooxygenation of alkenes adsorbed on dye-supported zeolites has recently attracted considerable attention due to the significant enhancement of product regioselectivity.[1−7] Ramamurthy and co-workers have reported a remarkable change in regioselectivity in the photooxygenation of several geminal dimethyl trisubstituted alkenes adsorbed on thionin-supported alkali metal exchanged Y-zeolites compared to that in solution.[2−5] For example, intrazeolite reaction of 2-methyl-2-pentene (R = methyl in Scheme 1) with singlet

Scheme 1

oxygen affords regiospecifically only the secondary allylic hydroperoxide, whereas when the reaction takes place in solution, a 60/40 ratio of tertiary/secondary hydroperoxides is formed.

The dramatic change in the regioselectivity had been attributed originally to two independent models:[5] (i) steric factors inside the cavity place the bulkier alkyl group (R) of **1** in such a conformation that methylene hydrogens are unreactive and (ii) polarization of the alkene by interaction of the cation to the olefin double bond in such a way that the more substituted bears a partial positive charge. Thus, the electrophilic oxygen attacks the more nucleophilic disubstituted carbon, and hydrogen abstraction occurs at the geminal methyls forming the secondary hydroperoxide. More recently, Clennan and Sram[6] proposed a new mechanistic model based on the regioselectivity results in the photooxygenation of some tetrasubstituted alkenes. They argued that the alkali metal cation forms a complex with the pendant oxygen in the intermediate perepoxide which leads to greater

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(5) Ramamurthy, V.; Lakshminarasimhan, P. H.; Grey, C. P.; Johnston, L. *J. Chem. Soc., Chem. Commun.* **1998**, 2411−2418.
(6) Clennan, E. L.; Sram, J. P. *Tetrahedron Lett.* **1999**, *40*, 5275−5278.
(7) Sen, S. E.; Smith, S. M.; Sullivan, K. A. *Tetrahedron* **1999**, *55*, 12657−12698.

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positive charge on the carbon framework, while steric interactions between the cation and the alkyl substituents affect the stability of the transition states leading to the intermediate perepoxides.

To determine the relative reactivity of *syn* and *anti* methyl groups in the geminal dimethyl trisubstituted alkenes **1** and to shed some light on the reaction mechanism, we performed the photooxygenation of the specifically labeled alkenes **2** and **3** adsorbed on thionin-supported zeolite Na−Y. Preparation of **2** and **3** was accomplished in 97% and 96% geometrical purity, respectively, following the reactions sequence presented in Scheme 2. The results shown in
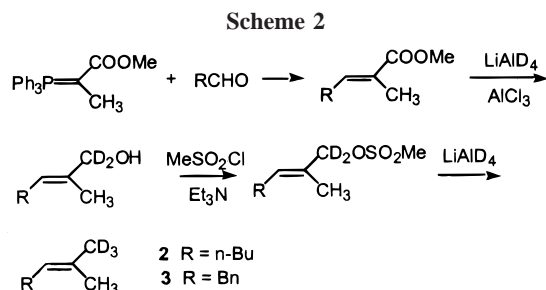
Scheme 2

Scheme 3 reveal that the methyl group in the less substituted side of both alkenes becomes significantly more reactive within zeolite compared to the reaction in solution (carbon tetrachloride/tetraphenylporphine).

In a typical experiment 1 g of dye-exchanged zeolite was added to 15 mL of dry hexane, followed by 10 mg of the alkene. Thus, the loading levels of alkenes[8] were approximately $n = 0.1-0.15$, to ensure that no "free" uncomplexed olefin would be oxidized. The slurry was irradiated with visible light (>450 nm). The loading level of thionin was maintained at lower than 1 dye molecule per 100 supercages as described in the procedure of Ramamurthy.[2] The reaction was almost complete within 5 min. Subsequently, 10 mL of moisted tetrahydrofuran was added and stirring was continued for 2 h. After filtration the solvent was evaporated under vacuum and the hydroperoxides were

analyzed. The mass balances in those experiments were found to be >85%, and the isolated yields were around 70%. Product distribution was measured by ^{1}H NMR integration of the appropriate peaks and by GC analysis of the allylic alcohols produced after reduction of initially formed allylic hydroperoxides with excess triphenylphosphine. The percentage reactivities of the allylic hydrogens were quite reproducible (the percentage deviation of three independent measurements was ±3%). The dye-supported zeolite was carefully treated with pyridine[9] prior to use to suppress the small extent of alkenes isomerization (∼2−3%) under the reaction conditions. It is notable that alkene **3** did not form any detectable amounts of the tertiary allylic hydroperoxide **3a** as had been reported previously.[3] However, a dye-zeolite sample left in the atmosphere for several days and then used led to the formation of increased amounts of **3a**. This points out the significance of the moisture on the stereoselectivity of the ene reaction. In the current experiments we used dye-zeolite samples that have been vacuum-dried for 3 h at 100 °C prior to use.

To model the cation−π interaction, we performed theoretical calculations on a simplified system. Our initial theoretical treatment indicates that interaction of the smallest alkali metal cation (lithium) with the simplest trisubstituted alkene, trimethylethylene, can form two distinct species in which the cation lies either on the less or on the more substituted side of the alkene *but not on top* of the carbon−carbon double bond (Figure 1). Calculations were performed with the GAUSSIAN 94 program package.[10] The theoretical treatment of the structures involved density functional theory (DFT) with the three-parameter hybrid functional of Becke[11] and the use of the Lee−Yang−Parr correlation functional (B3LYP).[12] The level of the calculations used herein was B3LYP/6-31G*. Many different starting geometries were used; however, after the optimizations, we found the two almost isoenergetic local minima presented in Figure 1. Similar results were found with the MP2 method and the same basis set. The MP2 method was used recently by Haw and co-workers to model the adsorption of benzene into zeolite LiZSM-5.[13] Surprisingly, even for the symmetrical tetramethylethylene, the structure in which Li^{+} lies toward

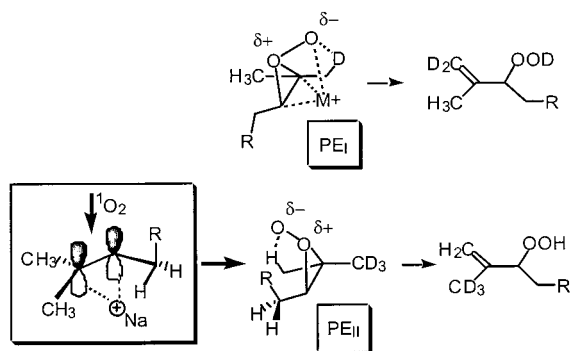**Scheme 3.** Photooxidation of Alkenes **2** and **3** in Thionin-Supported Zeolite Na−Y or in Solution
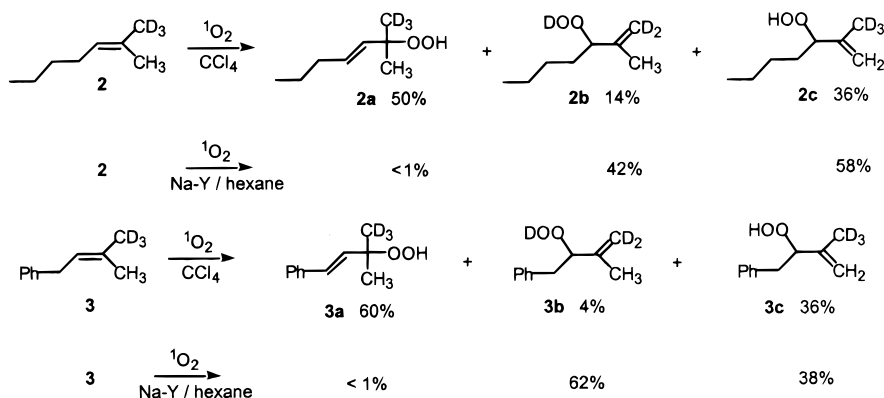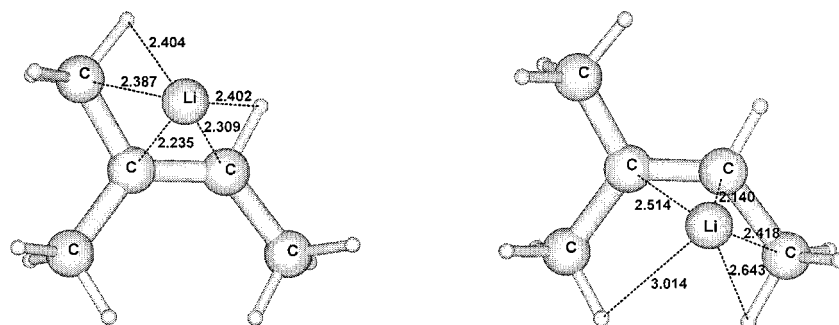
Figure 1. Calculated structures of Li$^+$ binding to trimethylethylene (lithium cation lies above the olefinic plane at the approximate distance of 2 Å).

the *cis* methyl groups was calculated to be more stable by 1 kcal/mol than that in which the cation sits on top in the middle of the C−C double bond.

On the basis of the experimental results and the theoretical calculations, we propose in Scheme 4 a model that can

Scheme 4[a]

[a] Cation is omitted in the structure of PE$_{II}$.

explain the regioselectivity in the intrazeolite photooxygenation of the geminal dimethyl trisubstituted alkenes. We view the reaction as proceeding through the intermediacy of an irreversible perepoxide or an exciplex with the structural

requirements of a perepoxide as is evident from the lack of a primary isotope effect in the photooxygenation of *cis*-tetramethylethylene-d_6.[6] For trisubstituted alkene such as **1**, the alkali metal cation binds to the double bond, forming two species either to the more or to the less substituted side of the alkene. The cation−double bond interaction is strong,[14] and it is likely to play a significant role in the stability of the transition states of the hydroperoxidation reaction. Recently, it was calculated that in the gas phase the Na$^+$−ethylene interaction is exothermic by 12.7 kcal/mol, and the cation sits in the middle of the double bond.[15]

The incoming oxygen can form the four possible intermediates in which the singlet oxygen and cation can be placed in the same or at different sides of the double bond. Considering the electrostatic interaction of the negatively charged pendant oxygen of the perepoxide to the cation,[6] we assume that the intermediates in which the oxygen is placed on the same side of the alkene as the cation are the most favorable. In the transition state for the formation of perepoxide PE$_I$, oxygen interacts simultaneously with one allylic hydrogen (D in the present case) and the positively charged cation. Therefore, it gains significant stabilization. It is likely that in the transition state leading to PE$_I$, the cation has moved from its original position in the complex with the olefin, resulting in a more efficient interaction with the negatively charged oxygen atom. On the other hand, when the cation binds on the more substituted side of the alkene, steric factors place the alkyl group in a conformation away from the cation as has been proposed by Ramamurthy.[2] Thus, in the transition state leading to PE$_{II}$, oxygen interacts also with the cation and one allylic hydrogen (from the methyl group), because methylene hydrogens have an unfavorable conformation. PE$_I$ leads to D abstraction from the *anti* allylic methyl group, while PE$_{II}$ leads to the ene product formed by hydrogen abstraction only from the *syn* allylic methyl group. On the other hand, in the absence of the alkali metal cation, a transition state leading to the formation of the perepoxide on the more substituted side of the alkene is more

(8) For the calculation of the loading levels, see: Zhou, W.; Clennan, E. L. *J. Am. Chem. Soc.* **1999**, *121*, 2915−2916.

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(14) For a review on cation−π interactions, see: Ma, J. C.; Dougherty, D. A. *Chem. Rev.* **1997**, *97*, 1303−1325.

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favorable, because singlet oxygen has the ability to interact simultaneously with two allylic hydrogens and leads to the expected "*cis* effect" selectivity.[16] Within the alkali metal exchanged zeolite, however, the transition states leading to PE_I and PE_{II} appear to have similar stabilizing interactions; thus they are close in energy.

For alkene **3**, theoretical calculations show that the phenyl group and the double bond are strongly bound to the cation in such a conformation that the benzylic hydrogens have an unfavorable geometry for interaction with the incoming oxygen, by not being perpendicular to the olefinic plane (see figure in Supporting Information). Furthermore, the cation sits almost on top of the disubstituted olefinic carbon and cannot interact efficiently with the oxygen placed either on the more or on the less substituted side of **3**. Thus, in the transition state leading to the formation of the intermediate on the more substituted side of **3**, oxygen interacts with only one allylic methyl hydrogen. Therefore, the perepoxide on the less substituted side of the alkene, where again oxygen interacts with one allylic hydrogen from the methyl group, is formed substantially. Similar *anti* "*cis* effect" selectivity is observed for trisubstituted alkenes that do not have the capability for a simultaneous interaction of singlet oxygen with two allylic hydrogens on the more substituted side of

the alkene.[17] The model we proposed in this Letter is a working hypothesis; however, so far we cannot find a better alternative that fits the experimental results.[18]

Theoretical calculations are currently underway to understand the nature of the cation$-\pi$ interaction for several nonsymmetrical alkenes and to locate the possible transition states of perepoxide formation in the reaction of $^1O_2$ with trimethylethylene bound to a Li^+.

Supporting Information Available: Four ^{1}H NRM spectra of the photooxygenation reactions and two figures showing the Li^+ interactions with **3**. This material is available free of charge via the Internet at http://pubs.acs.org.

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(18) **Note added in proof:** After this manuscript had been submitted we were informed by professor E. L. Clennan of some results similar to those reported here. We thank him for a prepublication copy of his manuscript. Clennan, E. L.; Sram, J. P. *Tetrahedron*, in press.