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Theoretical Study on Highly Active Bifunctional Metalloporphyrin Catalysts for the Coupling Reaction of Epoxides with Carbon Dioxide

Jun-ya Hasegawa,*[a] Ray Miyazaki,[a] Chihiro Maeda,*[b] and Tadashi Ema*[b]

Supporting information for this article is given via a link at the end of the document.

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Abstract: Highly active bifunctional metalloporphyrin catalysts were developed for the coupling reaction of epoxides with CO₂ to produce cyclic carbonates. The bifunctional catalysts have both quaternary ammonium halide and the metal center. To elucidate the roles of these catalytic groups, DFT calculations were performed. Control reactions using tetrabutylammonium halide as a catalyst were also investigated for comparison. In the present article, the results of our computational studies are overviewed. The computational results are consistent with the experimental data and are useful for elucidating the structure–activity relationship. The key features responsible for the high catalytic activity of the bifunctional catalysts are as follows: (1) the cooperative action of the halide anion (nucleophile) and the metal center (Lewis acid), (2) the near-attack conformation leading to the efficient opening of the epoxide ring in the rate-determining step, and (3) the conformational change of the quaternary ammonium cation to stabilize various anionic species generated during catalysis in addition to the robustness (thermostability) of the catalysts.

1. Introduction

Carbon dioxide (CO₂) is an inexpensive and abundant C1 source. It is desirable to develop efficient and useful methods for the conversion of CO₂ into value-added chemicals. One of the most useful reactions is the catalytic coupling reaction of CO₂ with epoxides to produce cyclic carbonates because the products can be used as electrolytes in lithium-ion secondary batteries and as raw materials for polycarbonates and because the reaction exhibits high atom efficiency (Figure 1a). Various catalysts, including metalloporphyrins, have been developed. The rigid porphyrin framework enables the introduction of various metal ions and functional groups. We have reported highly active bifunctional metalloporphyrin catalysts with the quaternary ammonium halide groups (Figure 1c). The bifunctional catalysts have two catalytic groups: one is quaternary ammonium halide (nucleophile) at the meta positions of the meso-phenyl groups, and the other is the central metal ion (Lewis acid). The epoxide is activated by metal-coordination to facilitate nucleophilic attack as represented by Figure 1b. The bifunctional metalloporphyrins showed very high turnover frequencies (TOF) and turnover numbers (TON) (Figure 1c).

Recently, density functional theory (DFT) computational studies were published for the coupling reaction of epoxides with CO₂ to produce cyclic carbonates. For example, Sun and Zhang studied alkylmethylimidazolium chloride catalysts and pointed out that the initial ring-opening reaction is the rate-determining step. They also pointed out that hydrogen bonding between the epoxide and the imidazolium cation can significantly reduce the activation barrier. However, most of the theoretical studies were focused on two-component catalytic systems. Therefore, the comparison of the optimized structures between the bifunctional porphyrin catalysts and the two-component catalysts provided significant and useful insight into the origin of the structure–activity relationship.

Here we summarize our theoretical studies based on the DFT calculations on the coupling reaction of epoxides with CO₂ using the highly active bifunctional metalloporphyrin catalysts. We also describe the mechanism for the reaction catalyzed by tetrabutylammonium halide (TBAX), such as TBA chloride (TBAC), TBA bromide (TBABr), and TBA iodide (TBAI). The use
of these simple catalysts enabled us to deeply understand the catalytic reaction although TBAX is much less efficient than the bifunctional metalloporphyrin catalysts. The origins of the high catalytic activity of the bifunctional catalysts are (1) the cooperative action of the halide ion (nucleophile) and the metal center (Lewis acid), (2) the near-attack conformation leading to the efficient opening of the epoxide ring in the rate-determining step, and (3) the conformational change of the flexible quaternary ammonium cation to stabilize various anionic species generated during catalysis in addition to the robustness (thermostability) of the catalysts.

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2. Computational details

DFT calculations were performed at the B3LYP/6-31G* level. The solvation effect was included with the self-consistent reaction field (SCRF) model (polarized continuum model[15] with the solvent parameters for Et2O). In the structural optimization, frequency calculations were performed for all the stationary points. On-the-fly ab initio molecular dynamics calculations (AIMD)[16] were carried out on the B3LYP/3-21G and semi-empirical PM3[17] potential energy surfaces. Solvent effect at the SCRF level was considered for the B3LYP surface, but not for the PM3 one because the SCRF calculation was unavailable for the PM3 method. Temperature was set to 500 K. Atomic population was calculated with natural population analysis.[18] All the calculations were performed with the Gaussian 09 package.[19]

3. Tetrabutylammonium Halides

3.1. Potential Energy Profile

The common features of the catalytic mechanism of these quaternary ammonium halides were reported in previous studies.[6-8] In our study,[9] DFT calculations on the TBAX-catalyzed reactions were performed along the catalytic cycle shown in Figure 2 using propylene oxide (PO) as a model substrate. Figure 3 shows the potential energy profile for the transformation of PO to propylene carbonate (PC) using TBAC, TBAB, or TBAI as a catalyst. In the reactant state (R), the halide anion forms an ion pair with the TBA cation. In the ring-opening transition state (TS1), however, PO is located between the TBA cation and the halide anion. Although this geometry is energetically unfavorable owing to the separation of the ion pair, the TBA cation is used to stabilize the negative charge of the O atom in TS1. The resulting intermediate IM1 then undergoes CO2 insertion at the O atom. The subsequent ring-closing reaction takes place via transition state TS2 to give the product (P).
3.2. Electrostatic Stabilization Effect

The initial ring-opening reaction is the rate-determining step because it has the highest energy and the largest energy barrier. The activation energy increases in the order TBAC (23.3 kcal/mol) < TBAB (26.5 kcal/mol) < TBAI (27.2 kcal/mol). The relative potential energy of IM1 also increases in the order TBAC (17.4 kcal/mol) < TBAB (20.7 kcal/mol) < TBAI (26.6 kcal/mol), and IM2 also shows the same trend. This tendency can be explained in terms of the stability of the leaving group. The I⁻ ion is the best leaving group, which is followed by Br⁻ and then Cl⁻. This order is also related to the C–X bond energy. According to the literature, the bond energies for C–Cl, C–Br, and C–I are 95, 67, and 50 kcal/mol, respectively.

3.3. Orientation of Epoxide Molecule

Figure 5 shows the changes of the potential energy and the atomic charges of the Cl and O atoms upon nucleophilic attack on PO by TBAC, demonstrating the importance of the orientation of the PO molecule. Figure 5a simulates the ring opening by the Cl⁻ ion bound at the same position as that in the R state (see Figure 3). In this case, the O atom of PO is directed away from the TBA cation. The negative charge of Cl⁻ is shifted to the O atom as the C–Cl distance is shortened to 2.5 Å. The potential energy further increases up to a C–Cl distance of 1.9 Å, which is the ordinary C–Cl bond length; however, no stabilization arising from the C–Cl bond formation can be seen (Figure 5a). This is because the O atom (negative charge) is far from the TBA cation. In contrast, when the epoxide is inserted between the TBA cation and the Cl⁻ ion before opening the epoxide ring, the O atom of PO can be directed toward the TBA cation. In this case, the negative charge of the Cl⁻ is shifted to the O atom of PO, as shown in Figure 5b. Upon formation of the C–Cl bond, the potential energy decreases as shown in Figure 5b.
4. Bifunctional Metalloporphyrin Catalysts

4.1. Potential Energy Profile

DFT calculations were performed along the catalytic cycle shown in Figure 6. Monosubstituted Mg(II) porphyrins 1a, 1b, and 1c with different halide anions were used as model catalysts, and PO was used as a model substrate. The potential energy profile is shown in Figure 7, and the transition state and intermediate structures for the 1b-catalyzed reaction are given in Figure 8.\[3a,3b\] The catalytic reaction starts from the R state (Figures 6 and 7) in which the alkyl chain adopts a moderately stretched conformation (Figure 8a). The ring-opening reaction takes place, and intermediate I1 is formed via transition state I1_TS. Interestingly, the calculated activation energies ($E_a$) increase in the order Br$^-$ (13.5 kcal/mol) < Cl$^-$ (16.1 kcal/mol) < I$^-$ (20.2 kcal/mol); the reaction catalyzed by 1b with Br$^-$ has the smallest activation energy. This trend, which is different from that observed for TBAX (Figure 3), is in good agreement with the experimentally observed yield and TON.\[3a,3b\] It is likely that the quaternary ammonium cation can stabilize the Br$^-$ ion in the most complementary and efficient manner in transition state I1_TS.\[3b\]

As shown in Figures 8a and c, the negative charge of the Br$^-$ ion in the R state is shifted to the O atom in the I1 state. Because the charged species are separated, the quaternary ammonium cation undergoes a conformational change to a bent form, and the distance between the N and O atoms becomes closer. Starting with the lowest-energy structure of the stretched form, the AIMD trajectory shows a smooth conformational change to the bent form (Figure S2). Intermediate I1 undergoes CO$_2$ attack at the negatively charged O atom. This C–O bond formation is accompanied by little or no activation barrier to formation.
reach the second intermediate \( I_2 \). The final step is the ring-closing reaction to give the product. The activation energies for \( P_{\text{TS}} \) are 18.0 kcal/mol (Cl), 17.1 kcal/mol (Br), and 12.3 kcal/mol (I). This order corresponds to the order of the C–X bond energy and also to the nature of the leaving group.

We also calculated the energies for the binding of PO and PC to the metal center. The calculated binding energy of the product, PC, is 10.1 kcal/mol, while that of the reactant, PO, is 11.2 kcal/mol. This result strongly suggests that the replacement of the product by the reactant easily takes place.

Figure 7. Potential energy profiles for the 1a, 1b, and 1c-catalyzed reactions of propylene oxide (PO) with CO\(_2\). The relative energies based on reactant \( R \) (stretched form) are given in kcal/mol. The energy of CO\(_2\) is included in the former steps where CO\(_2\) does not appear explicitly. The stretched and bent forms designated here can be seen in Figure 8. Reprinted (adapted) with permission from (T. Ema, Y. Miyazaki, J. Shimonishi, C. Maeda, and J. Hasegawa, J. Am. Chem. Soc. 2014, 136, 15270.). Copyright (2014) American Chemical Society.
Figure 8. Optimized structures of (a) reactant \( R \) (stretched form), (b) transition state \( I_1\_TS \), (c) \( I_1 \) (stretched form), (d) \( I_1 \) (bent form), (e) transition state \( I_2\_TS \), (f) \( I_2 \), (g) transition state \( P\_TS \), and (h) product \( P \) in the 1b-catalyzed reaction of propylene oxide (PO) with \( \text{CO}_2 \). Reprinted (adapted) with permission from (T. Ema, Y. Miyazaki, J. Shimonishi, C. Maeda, and J. Hasegawa, J. Am. Chem. Soc. 2014, 136, 15270.). Copyright (2014) American Chemical Society.
4.2. Near-attack Conformation

The advantage of the bifunctional metalloporphyrin is structural resemblance between R and I1_TS (Figures 8a and b). Because a slight shift of the halide anion to PO in R can reach transition state I1_TS, we call the R state “near-attack conformation”. The quaternary ammonium cation takes the “concave” conformation in R and I1_TS. We consider that this conformation increases probability to pass the activation barrier.

In contrast, in the case of TBAX, PO and X⁻ in R are located in different anion-binding sites of the TBA cation. As a result, PO is distant from the X⁻ ion. Even if the X⁻ ion and PO are close to each other, PO needs to intervene between the TBA cation and the X⁻-ion with an energy cost of 8 kcal/mol.

In a recent report, the role of the near-attack conformation was also proposed for the same reaction in a silica-supported niobium complex. Because the Nb complexes on the surface are in close proximity to each other, the neighboring Nb complexes bind both the epoxide and the halide anion in an ideal conformation for the ring-opening reaction.

4.3. Stability of the Ring-opened Intermediate

The Mg(II) ion of the porphyrin acts as a Lewis acid to stabilize both transition state I1_TS and intermediate I1. For example, as shown in Table 1, the potential energies for I1_TS and I1 in the 1b-catalyzed reaction are 13.5 and 8.0 kcal/mol, respectively. These values are much smaller than the corresponding values in the TBAB-catalyzed reaction (26.5 and 20.7 kcal/mol). Furthermore, intermediate I1 undergoes the conformational change of the quaternary ammonium cation from the stretched to bent forms. Table 1 indicates that the energetic benefit caused by this conformational change is 1.0–4.0 kcal/mol, depending on the halide anion. Because the ring-opened intermediates, IM1 for TBAX and I1 for 1a–c, undergo CO₂ attack, their lifetimes would be important for catalytic activity. As seen in Figure 5, the potential energy of the ring-opened intermediate is sensitive to the stabilization of the negatively charged O atom. Therefore, this is another advantage of the bifunctional metalloporphyrins over TBAX because in the former case, various anionic species generated during catalysis can be stabilized by both the metal center and the flexible quaternary ammonium cation (Figure 8).

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4.4. Metal Ion in the Porphyrin Ring

DFT calculations on bifunctional Zn(II) complexes were also performed, and the results were compared with that of the corresponding Mg(II) complexes. In the case of the Zn(II) complex, the calculated Eₚ value for the ring-opening step (14.3 kcal/mol) was slightly greater than that of the Mg(II) complex (13.5 kcal/mol). This result is in good agreement with the experimental result; the yield and TON for the Zn(II) catalysts are slightly lower than those of the Mg(II) counterparts. This difference might arise from the charge on the metal ion in I1_TS and I1. According to the NPA analysis, however, the atomic charge of Zn(II) is about +1.3 during catalysis, and this amount is only slightly less than that of the Mg(II) catalyst. Moreover, there is no significant difference in the optimized structures between the Zn(II) and Mg(II) complexes. The electronegativity or oxophilicity of the two metal ions may be important for the difference in catalytic activity. The thermostability of the Zn(II) catalyst is obviously higher than that of the Mg(II) catalyst. The TON of a Zn(II) catalyst reached 240,000 at 96% conversion after the five-day reaction.

4.5. Effect of ortho-, meta-, and para-Substitutions on Catalytic Activity

Considering the important role of the quaternary ammonium cation, the positional isomers of the bifunctional metalloporphyrins were synthesized and compared. As a result, meta-substituted catalysts showed the highest TONs in the experiments, followed by the corresponding para isomer and then the ortho isomer. To account for this experimental result, we performed the DFT calculations and compared the potential energy profiles.

The meta isomer has the smallest activation energy, which agrees with the experimental observation. The Eₚ values for the ring-opening reaction in the ortho-, meta-, and para-substituted catalysts are 16.4, 14.3, and 17.0 kcal/mol, respectively. In the optimized structure of the para isomer in the R state, the quaternary ammonium bromide group is stretched and directed away from the metal-coordination site. As a result, the alkyl chain linker undergoes a substantial conformational change to a reactive conformation that is 2.9 kcal/mol higher than R. As for the ortho isomer, the calculated activation energy seems to be
underestimated probably due to the insufficiency of the simplified model. In the optimized structures, the quaternary ammonium cation in the ortho isomer significantly invades the space of other quaternary ammonium cations on the opposite side of the porphyrin ring.

5. Summary

Highly active and robust metalloporphyrin catalysts were developed for the coupling reaction of epoxides with CO$_2$.[3] The bifunctional metalloporphyrins have the quaternary ammonium halide groups via the hexamethylene linker carefully optimized for the best catalytic activity. To elucidate the roles of the catalytic groups, we performed DFT calculations and obtained the potential energy profiles together with the optimized structures of the reactants, transition state, intermediate, and the product. In addition, we studied the reactions catalyzed by TBAX for comparison. Computational studies were useful for clarifying the structure--activity relationship. The origins of the high catalytic activity of the bifunctional metalloporphyrin catalysts can be summarized as follows: (1) the cooperative action of the halide ion (nucleophile) and the metal center (Lewis acid), (2) the near-attack conformation leading to the efficient opening of the epoxide ring in the rate-determining step, and (3) the conformational change of the flexible quaternary ammonium cation to stabilize various anionic species generated during catalysis in addition to robustness (thermostability) of the catalysts.

Acknowledgements

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Keywords: Carbon dioxide fixation • Cyclic carbonates • DFT calculation • Epoxides • Porphyrinoids
Highly active bifunctional metalloporphyrin catalysts were developed for the reactions of epoxides with CO$_2$ to produce cyclic carbonates. The bifunctional catalysts have the metal center and the quaternary ammonium halide. DFT calculations were performed to elucidate the reaction mechanism. The results were consistent with the experimental data and useful for understanding the structure–activity relationship.