Mechanism of Cyclic Carbonate Synthesis from Epoxides and CO₂

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There is currently much interest in the use of carbon dioxide as a chemical starting material, both to provide an alternative feedstock to fossil fuels and to help to mitigate global warming.[1] For the latter application, it is desirable that processes are developed which operate at atmospheric pressure and at or near room temperature. One reaction attracting significant attention in this respect is the 100% atom-economical synthesis of cyclic carbonates by the insertion of carbon dioxide into an epoxide (Scheme 1).

Though most current catalysts for this process require the use of high reaction temperatures and/or high pressures of carbon dioxide,[1,2] we recently reported the development of bimetallic aluminum(salen) complex 1, which when used in conjunction with tetrabutylammonium bromide constitutes the only catalyst system capable of catalyzing the insertion of carbon dioxide into terminal epoxides at 1 atm (760 mmHg) and at ambient temperature.[3] These extremely mild reaction conditions have allowed us to carry out the first mechanistic study of this important reaction, revealing a previously unanticipated role for the tetrabutylammonium bromide in the catalytic cycle.

The mechanistic studies were initiated with a detailed analysis of the reaction kinetics. Our previous work with catalyst 1 was carried out under solvent-free conditions,[3] and all attempts to carry out reactions in conventional solvents failed to produce any cyclic carbonate product. However, catalyst 1 is known to catalyze the synthesis of propylene carbonate from propylene oxide. Therefore, propylene carbonate, which is a liquid at room temperature, must be a suitable solvent for cyclic carbonate synthesis. Based on this, we developed standard conditions for the kinetic study in which styrene oxide served as the substrate and propylene carbonate as the solvent. The progress of these reactions could be conveniently monitored either by analysis of reaction samples by GC or by in situ FTIR.

The general form of rate equation is given by Equation (1). By working under conditions where carbon dioxide is present in large excess, and noting that the concentrations of catalyst 1 and tetrabutylammonium bromide will be effectively constant during the reaction, this can be simplified to Equation (2). In the event, the reactions followed first-order kinetics,[4] and by varying the concentrations of carbon dioxide, catalyst 1, and tetrabutylammonium bromide, we could determine the rate equation as Equation (3).

The first-order dependence on each reactant/catalyst concentration except tetrabutylammonium bromide was anticipated, but the second-order dependence of the rate on the tetrabutylammonium bromide cocatalyst concentration was unexpected and implies that two separate molecules of tetrabutylammonium bromide are involved in the mechanism in a catalytic cycle before the rate-determining step. It was also noted that reactions carried out at very low concentrations of tetrabutylammonium bromide had an induction period (Figure 1), though this was not apparent in reactions carried out at higher concentrations of tetrabutylammonium bromide.

It is well established[5] that one role of tetrabutylammonium bromide and related species in cyclic carbonate synthesis is to open the epoxide ring to form a bromo-alkoxide (which can be stabilized by coordination to a metal catalyst such as 1, which then reacts with carbon dioxide and cyclizes to give the cyclic carbonate with regeneration of the tetrabutylammonium bromide catalyst (Scheme 2). However, the kinetic data suggested that the tetrabutylammonium bromide was also involved in the mechanism in a second way.

Additional evidence on the role of tetrabutylammonium bromide came from reactions aimed at investigating the reusability of catalyst 1 and tetrabutylammonium bromide. These reactions were carried out under solvent-free conditions with propylene oxide as substrate and using 2.5 mol% of both salen complex 1 and tetrabutylammonium bromide as catalysts. After a reaction time of three hours under a carbon dioxide atmosphere, the propylene carbonate was distilled...
from the reaction flask and replaced with a new batch of propylene oxide and the process repeated. The purity of the propylene carbonate formed in these reactions was assayed by GC, and a second compound was sometimes found to be present. This was identified on the basis of its EI GC–MS as tributylamine. The amount of tributylamine detected decreased as the catalysts were reused and eventually catalytic activity decreased. However, upon addition of more tetrabutylammonium bromide the catalytic activity was restored, and tributylamine was again detected in the propylene carbonate product. Control experiments showed that the tributylamine was not formed during the distillation process or by decomposition of tetrabutylammonium bromide within the GC–MS. Thus it appears that under the reaction conditions, tetrabutylammonium bromide decomposes to tributylamine by an $S_N2$[6] and/or E2 [7] mechanism. That tributylamine is a key component in the reaction and not just a decomposition product was confirmed by kinetics experiments carried out in the presence of catalyst 1, tetrabutylammonium bromide, and tributylamine. These experiments indicated that the rate of reaction depends on the concentration of all three species; and non-integer orders with respect to tetrabutylammonium bromide and tributylamine were observed, which is consistent with their interconversion under the reaction conditions.

Amines are well known to form carbamate salts with carbon dioxide;[1, 8] indeed this is the basis of many processes for the capture of carbon dioxide. These carbamate salts can be considered as activated forms of carbon dioxide and, compared to carbon dioxide itself, will also coordinate more readily to a metal complex such as 1. Nucleophilic amines such as 4-dimethylaminopyridine (DMAP) have also been used to catalyze the formation of cyclic carbonates,[9] though formation of a trialkylamine in situ as part of the catalytic role of a tetraalkylammonium salt has not previously been considered. On the basis of this evidence, a catalytic cycle explaining how bimetallic complex 1 and tetrabutylammonium bromide combine to form a uniquely active system for cyclic carbonate can be proposed (Scheme 3).
absence of added tributylamine) implies that formation of intermediate 4 is the rate-determining step of the catalytic cycle.

Given the widespread use of tetraalkylammonium salts (and related species such as tetraalkylphosphonium salts) as catalysts and cocatalysts in the formation of cyclic carbonates, it is likely that the roles of the tetrabutylammonium bromide outlined in Scheme 3 have general applicability to other catalyst systems. This is especially true of processes that operate at elevated temperatures as this is known to favor the conversion of tetraalkylammonium halides into trialkylamines.[6,7]

In summary we have carried out a detailed kinetics analysis of cyclic carbonate synthesis catalyzed by the bimetallic aluminum(salen) complex. Analysis of cyclic carbonate synthesis catalyzed by the proposed a new catalytic cycle that fully explains the role of tetrabutylammonium bromide; this suggests that bromide ionification of tributylamine in the reaction mixture, we have observed second-order dependence of the reaction rate on tetrabutylammonium bromide concentration and the identification of tributylamine in the reaction mixture, we have proposed a new catalytic cycle that fully explains the role of the tetrabutylammonium bromide cocatalyst.

Keywords: aluminum · carbon dioxide fixation · homogeneous catalysis · oxygen heterocycles · Schiff bases

[1] a) A. Baiker, Appl. Organomet. Chem. 2000, 14, 751–762; b) H. Arakawa, M. Aresta, J. N. Arnor, M. A. Barteau, E. J. Beckman, A. T. Bell, J. E. Bercau, C. Creutz, E. Dinjus, D. A. Dixon, K. Domcn, D. L. DuBois, J. Eckert, E. Fujita, D. H. Gibson, W. A. Goddard, D. W. Goodman, J. Keller, G. J. Kubas, H. H. Kung, J. E. Lyons, L. E. Manzer, T. J. Marks, K. Morokuma, K. M. Nicholas, R. Periana, L. Que, J. Rostrup-Nielson, W. M. H. Sachtlcr, L. D. Schmidt, A. Sen, G. A. Somorjai, P. C. Stair, B. R. Stults, W. Tumns, Chem. Rev. 2001, 101, 953–996; c) M. Aresta, A. Dibenedetto, Catal. Today 2004, 98, 455–462; d) I. Omac, Catal. Today 2006, 115, 33–52; e) R. Zevenhoven, S. Eloneva, S. Teir, Catal. Today 2006, 115, 73–79; f) T. Sakakura, J.-C. Choi, H. Yasuda, Chem. Rev. 2007, 107, 2365–2387; g) M. Aresta, A. Dibenedetto, Dalton Trans. 2007, 2975–2992.

[2] a) D. J. Darensebourg, M. W. Holtcamp, Coord. Chem. Rev. 1996, 153, 155–174; b) A.-A. G. Shaiik, S. Sivaram, Chem. Rev. 1996, 96, 951–976; c) M. Yoshida, M. Ihara, Chem. Eur. J. 2004, 10, 2886–2893; d) J. Sun, S.-i. Fujita, M. Arai, J. Organomet. Chem. 2005, 690, 3400–3407.

[3] J. Meléndez, M. North, R. Pasquale, Eur. J. Inorg. Chem. 2007, 3323–3326.

[4] See the Supporting Information for details.

[5] a) N. Kihara, Y. Nakawaki, T. Endo, J. Org. Chem. 1995, 60, 473–475; b) X.-B. Lu, H. Wang, R. He, J. Mol. Catal. A 2002, 186, 33–42; c) V. Caló, A. Nacci, A. Monopoli, A. Fanizzi, Org. Lett. 2002, 4, 2561–2563; d) K. Kossey, N. Koseva, K. Troev, J. Mol. Catal. A 2003, 194, 29–37; e) J.-W. Huang, M. Shi, J. Org. Chem. 2003, 68, 6705–6709; f) J. Sun, S.-i. Fujita, B. M. Bhanage, M. Arai, Catal. Commun. 2004, 5, 83–87; g) J. Sun, S.-i. Fujita, B. M. Bhanage, M. Arai, Catal. Today 2004, 93–95, 383–388; h) J. Sun, S. I. Fujita, F. Zhao, M. Arai, Green Chem. 2004, 6, 613–616; i) F. Li, L. Xiao, C. Xia, B. Hu, Tetrahedron Lett. 2004, 45, 8307–8310; j) J. Sun, S.-i. Fujita, F. Zhao, M. Arai, Appl. Catal. A 2005, 287, 221–226; k) W. N. Sit, S. M. Ng, K. Y. Kwong, C. P. Lau, J. Org. Chem. 2005, 70, 8583–8586; l) H. Xie, H. Duan, S. Li, S. Zhang, New J. Chem. 2005, 29, 1199–1203; m) T. Takahashi, T. Watahiki, S. Kitazume, H. Yasuda, T. Sakakura, Catal. Commun. 2006, 1664–1666; n) H. Xie, S. Li, S. Zhang, J. Mol. Catal. A 2006, 259, 30–34; o) H. Jing, T. Chang, L. Jin, M. Wu, W. Qiu, Catal. Commun. 2007, 8, 1630–1634; p) L.-F. Xiao, F.-W. Li, J.-J. Peng, C.-G. Xia, J. Mol. Catal. A 2006, 253, 265–269; q) J. Sun, L. Wang, S. Zhang, Z. Li, X. Zhang, W. Dai, R. Mori, J. Mol. Catal. A 2006, 256, 295–300; r) M. Ramin, N. van Vegten, J.-D. Grunwaldt, A. Baiker, J. Mol. Catal. A 2006, 258, 165–171; s) Y. Du, J.-Q. Wang, Y.-J. Chen, F. Cai, J.-S. Tian, D.-L. Kong, L.-N. He, Tetrahedron Lett. 2006, 47, 1271–1275; t) J. He, T. Wu, Z. Zhang, K. Ding, B. Han, Y. Xie, T. Jiang, Z. Liu, Chem. Eur. J. 2007, 13, 6992–6997; u) J. Sun, S. Zhang, W. Cheng, J. Ren, Tetrahedron Lett. 2008, 49, 3588–3591; v) S.-S. Wu, X.-W. Zhang, W.-L. Dai, S.-F. Yin, W.-S. Li, Y.-Q. Ren, C.-T. Au, Appl. Catal. A 2008, 341, 106–111.

[6] a) A. W. Hofman, Proc. R. Soc. London 1860, 10, 594–596; b) N. Collie, S. B. Schryver, J. Chem. Soc. 1890, 767–782; c) A. Zaki, H. Fahim, J. Chem. Soc. 1942, 270–272; d) J. E. Gordon, J. Org. Chem. 1965, 30, 2760–2763.

[7] a) W. Hanhart, C. K. Ingold, J. Chem. Soc. 1927, 997–1020; b) E. D. Hughes, C. K. Ingold, C. S. Patel, J. Chem. Soc. 1933, 526–530; c) J. de La Zerda, R. Neumann, Y. Sasson, J. Chem. Soc. Perkin Trans 2 1986, 823–826.

[8] L. Phan, J. R. Andreaitta, L. K. Horvey, C. F. Edie, A.-L. Luco, A. Mirchandani, D. J. Darensebourg, P. G. Jessop, J. Org. Chem. 2008, 73, 127–132.

[9] R. L. Paddock, S. T. Nguyen, J. Am. Chem. Soc. 2001, 123, 11498–11499; b) R. L. Paddock, S. T. Nguyen, Chem. Commun. 2004, 1622–1623; c) H. Jing, S. K. Edulji, J. M. Gibbs, C. L. Stern, H. Zhou, S. T. Nguyen, Inorg. Chem. 2004, 43, 4315–4327; d) M. Alvaro, C. Baleizao, E. Carbonell, M. El Ghoul, H. Garcia, B. Gigante, Tetrahedron 2005, 61, 12131–12139; e) G. A. Luinstra, G. R. Haas, F. Molnar, V. Bernhart, R. Eberhardt, B. Rieger, Chem. Eur. J. 2005, 11, 6298–6314; f) D. J. Darensebourg, C. C. Fang, J. L. Rogers, Organometallics 2004, 23, 924–927.

[10] Tributylamine had no significant catalytic activity (1.4% conversion after a reaction time of 21 h) in the absence of tetrabutylammonium bromide; this suggests that bromide rather than tributylamine opens the epoxide ring. See the Supporting Information for details.