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Azaphosphatranes as Structurally Tunable Organocatalysts for Carbonate Synthesis from CO_2 and Epoxides

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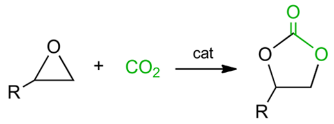
Supporting Information

ABSTRACT: Three azaphosphatranes were used as organocatalysts for the synthesis of cyclic carbonates from CO_2 and epoxides. They proved to be efficient single-component, metal-free catalysts for the reaction of simple or activated epoxides (styrene oxide, epichlorohydrin, glycidyl methyl ether) with CO_2 under mild reaction conditions, displaying high stability and productivity over several days of reaction. Substitution patterns on the catalyst were shown to affect activity and stability. Kinetic analysis allowed investigation of the reaction mechanism.

The development of catalytic processes for utilization of carbon dioxide (CO_2), a global-warming gas, is of growing interest for carbon management and sustainable development.[1,2] Carbon dioxide is a potentially inexpensive and abundant renewable C1 building block and is recognized to be environmentally benign (nontoxic, noncorrosive and nonflammable). In this regard, the efficient transformation of CO_2 under mild conditions into useful chemical compounds is very attractive from both an industrial and an academic viewpoint.[3−6] CO_2 is thermodynamically very stable, and its activation requires the use of high-energy substrates or electroreductive processes;[7,8] however, the synthesis of low-energy target molecules such as organic carbonates represents a promising alternative to overcome the thermodynamics. The cycloaddition of CO_2 to epoxides to produce five-membered cyclic carbonates (Scheme 1) is one of the few industrial synthetic processes that efficiently utilizes CO_2 as a raw material.[9−11]

Cyclic carbonates are widely used as electrolyte components in lithium batteries, polar aprotic solvents, and intermediates in the production of pharmaceuticals and fine chemicals.[12−14] In terms of "green chemistry" and "atom economy" this process is very attractive because CO_2 can be incorporated into epoxides with no formation of side products.[15]

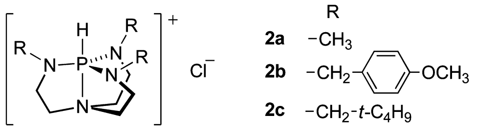
Scheme 1. Synthesis of Cyclic Carbonates from Epoxides and Carbon Dioxide



In the past decades, numerous catalysts have been developed for this purpose. Quaternary ammonium and phosphonium salts or alkali metal halides (e.g., KI) are typically used as homogeneous catalysts. Other homogeneous catalytic systems have also been reported to be effective in the production of cyclic carbonates.[16−18] Recent examples include $ZnBr_2(pyridine)_2$,[19] salen complexes such as Cr-salen-Cl/base,[20] ionic liquids such as imidazolium salts,[21] and polyfluoroalkyl phosphonium iodides.[22] However, in most of these cases, additives and/or cocatalysts as well as organic solvents are often needed. In addition, unsatisfactory activities, harsh reaction conditions, and the presence of toxic metals are still drawbacks that need to be overcome. Hence, the design of novel, metal-free catalysts with enhanced properties still remains to be developed toward effective CO_2 conversion.

The azaphosphatranes, which are the acidic counterparts of the well-known proazaphosphatrane superbases (also named Verkade's superbases)[23] possess several interesting features as potential catalysts for this reaction related to their charge, the relative ease and modular character of their syntheses, and their robustness (Chart 1). They contain a phosphorus atom, which is stabilized through proton-induced chelation by the tertiary nitrogen, rendering the phosphorus atom five-coordinate.[24] The presence of the free anion is helpful in a large number of catalytic processes,[25] but it is the structure of the cation, with the very stable partially charged proton ensconced in a large tunable lipophilic pocket along with the presence of several tertiary nitrogen atoms within the molecule, that makes this class of catalysts very interesting, particularly for the CO_2 activation reaction. A few synthetic applications of these molecules have been reported by Verkade's group.[26,27]

Chart 1. Structure of the Azaphosphatranes 2a−c



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Recently, we reported the first use of these protonated phosphonium moieties as highly active and robust phase transfer catalysts.[28]

In this contribution, we report on their activity as organocatalysts for cyclic carbonate synthesis from CO_2 and epoxides. We show that they are indeed efficient single-component, metal-free catalysts for this reaction, which display high stability and productivity over several days of reaction. We considered three azaphosphatranes with various electronic and steric properties, with Cl^- as counteranion, to explore the influence of the structural features on the catalytic behavior.

Methyl (**2a**), *p*-methoxybenzyl (**2b**), and *neo*-pentyl (**2c**) azaphosphatrane derivatives (Chart 1) were prepared in a two-step synthesis, which involved first a triple reductive alkylation of the appropriate aldehyde on the tris-(2-aminoethyl)amine followed by reaction with $PCl(NMe_2)_2$ (Scheme S1 in Supporting Information [SI]).[29,30] The effect of the catalyst structure on the catalytic performance was first investigated in detail using the coupling of styrene oxide (SO) with CO_2 to produce styrene carbonate (SC) as a model reaction, and we especially focused our attention on their initial activity. Given the long-term goal of producing low-pressure CO_2 activation catalysts, we initially chose to work under pressures of CO_2 close to atmospheric pressure with a catalyst loading of 1 mol %. Finally, to achieve significant and differentiable conversions at this low CO_2 pressure in useful time frames, the reaction was run at 100 °C.

The reaction of SO with CO_2 catalyzed by the methyl-substituted azaphosphatrane **2a** led to low carbonate yield (11%), and the conversion stopped after a few hours (Figure 1, curve 2a). The ^{31}P NMR spectra analysis of the crude mixture (Figures S1 and S4 in SI) showed, in addition to the catalyst signal at −11.0 ppm, the presence of two downfield signals at 7.3 and 5.6 ppm, suggesting some catalyst degradation which may originate from the insertion of CO_2 into the P−N bond, as previously reported for aminophosphane derivatives[31a] and also observed with CS_2.[31b,c]

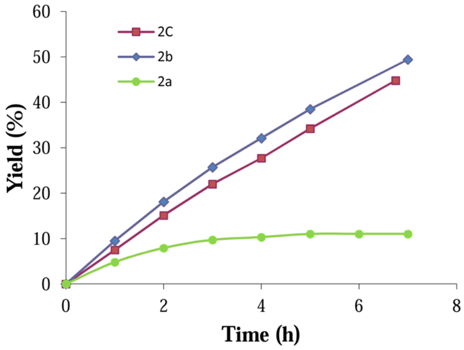


Figure 1. Initial kinetic profile of the catalytic coupling reactions of SO with CO_2. Conditions: SO (5.0 mmol), **2a−c** (0.05 mmol), CO_2 (1 atm), toluene (1 mL), 100 °C. Yields were determined by ^1H NMR using 2,4-dibromomesitylene (1.0 mmol) as an internal standard.

This result prompted us to investigate more sterically congested azaphosphatranes, hypothesizing that steric protection of the P−H site would improve catalyst stability under our reaction conditions. As expected, bulky *p*-methoxybenzyl (**2b**) and *neo*-pentyl (**2c**) azaphosphatranes gave satisfactory results with 50% yields after 7 h (Figure 1, curves b and c). The ^{31}P NMR spectra analyses of the crude mixtures issued from the runs with **2b** and **2c** each showed only the initial catalyst's P−H resonance at −12 and 2.1 ppm, respectively (Figures S5 and S6 in SI), supporting our assumption which connects their stability to the bulkiness around the N−P−H bonds (vide infra).

A second series of reactions was carried out with **2b** and **2c** under solvent-free conditions and a much higher substrate-to-catalyst ratio (1000:1) for a much longer period. The progress of each reaction was monitored by ^1H NMR analysis of aliquots taken every 24 h. After each 24-h period, an appropriate amount of SO was added to bring the substrate-to-catalyst ratio back up to 1000. A marked difference between **2b** and **2c** was clearly evidenced (Figure 2). The *p*-methoxybenzyl-substituted azaphosphatrane **2b** was initially active, but this activity decreased over the four-day test. The *neo*-pentyl-substituted catalyst **2c** showed an almost constant reactivity through the four-day experiment. After this period the crude reaction mixtures were analyzed by ^{31}P NMR spectroscopy. With **2b** several downfield signals, in addition to that of **2b**, were observed, whereas the spectrum with catalyst **2c** remained very clean (Figures S7 and S8 in SI).

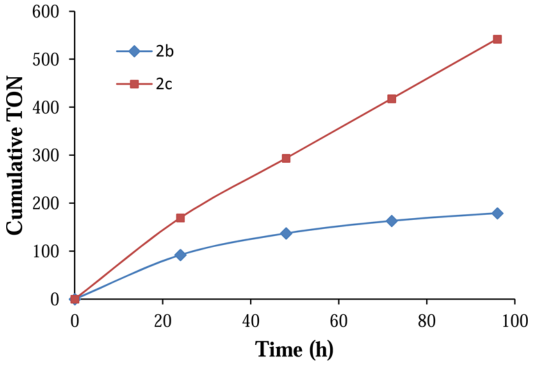


Figure 2. Effect of the azaphosphatrane substitution on catalyst stability. Conditions: SO (50.0 mmol), **2b** or **2c** (0.05 mmol), CO_2 (1 atm), 100 °C. TON were determined by ^1H NMR spectroscopy using 2,4-dibromomesitylene (2.0 mmol) as an internal standard.

Again, higher steric hindrance around the N−P−H core correlates with catalyst stability, after CO_2 insertion into the P−N bond. Further experiments showed that at lower temperature (80 °C) **2b** can also perform as a stable and productive catalyst (Figure 3). In order to produce significant turnovers at 80 °C, more reactive substrates (i.e., epichlorohydrin and glycidyl

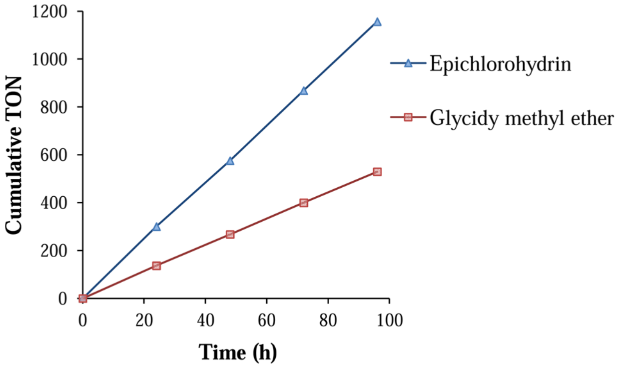
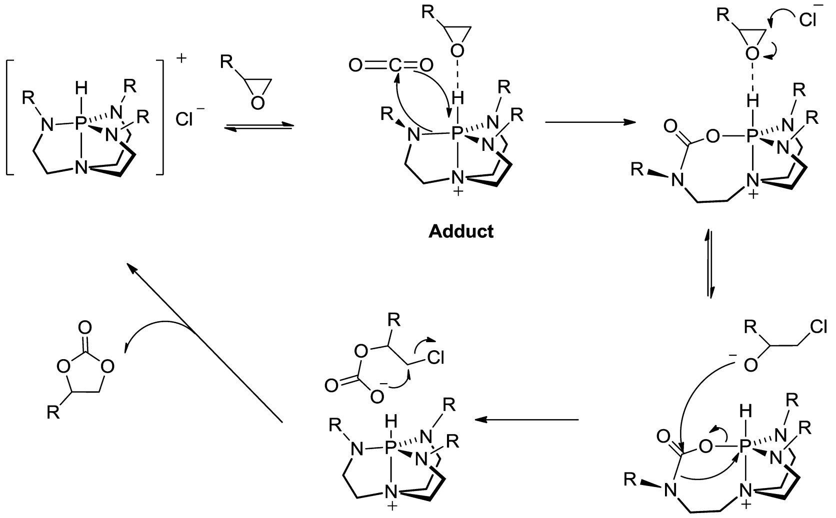


Figure 3. Activity of *p*-methoxybenzyl azaphosphatrane (**2b**) at 80 °C. Conditions: epoxide (50.0 mmol), **2b** (0.05 mmol), CO_2 (1 atm), 80 °C. TON were determined by ^1H NMR spectroscopy using 2,4-dibromomesitylene (2.0 mmol) as an internal standard.

Scheme 2. Proposed Mechanism for Cyclic Carbonates Synthesis Catalyzed by Azaphosphatrane Derivatives



methyl ether) were used. In this manner, **2b** produced high TON in a very steady fashion over several days (Figure 3), arriving at more than 1000 turnovers for epichlorohydrin after four days.

Insight into the reaction mechanism was obtained from a series of kinetic studies. In order to determine the order with respect to catalyst, the reaction was carried out without solvent, under 1 bar of CO_2 at 100 °C, and with four different catalyst loadings between 0.25 to 1.50 mol %. Normal first-order dependence on epoxide was observed over 5 h of reaction (Figure S9 in SI), and comparison of the observed rate constants for the four experiments indicated a first-order reaction in catalyst (Figure S10 in SI). Rates were also determined for a series of runs under varying concentrations of CO_2, produced by saturating the solution with a mixture of CO_2 and N_2 (10, 20, 50 and 100%) (Table S1 in SI). A first-order dependence on CO_2 was observed (Table S2 in SI). This is consistent with a rate-determining step involving both catalyst, epoxide, and CO_2.

Given these observations and literature precedents,[32,33] we propose the mechanism illustrated in Scheme 2. SO first forms an adduct with the catalyst through oxygen via a hydrogen bond to the phosphonium cation. A tricyclic phosphorylcarbamate structure is then obtained by insertion of CO_2 into the P−N bond. This species is highly reactive and very sensitive to hydrolysis and can lead to degradation as mainly observed with **2a**.[31a] The bulkier substituents in **2b** and **2c** act as protecting groups avoiding degradation. For this scheme, the observed first-order rate dependences on catalyst, CO_2, and SO seem to indicate that the formation of the adduct is in rapid equilibrium with free azaphosphatrane and SO and that the CO_2 activation step is rate determining. The reaction proceeds to product by the nucleophilic attack of the chloride at the secondary carbon of the epoxide and subsequent attack of the resultant alkoxide moiety on the activated carbon dioxide. The proximity of the two activated moieties might also suggest that these steps are concerted. Subsequent ring-closure would form the cyclic carbonate and regenerate the azaphosphatrane catalyst.

To conclude, this work features the use of azaphosphatranes as tunable alternatives to quaternary ammonium and/or phosphonium catalysts. It has been shown that they can exhibit high catalytic activity toward the formation of cyclic carbonates. The effect of azaphosphatrane substitution on catalytic activity was particularly investigated, and it was found that the bulkier *neo*-pentyl azaphosphatrane derivative **2c** was the most stable and active species. Detailed kinetic studies allowed us to propose a mechanism which implies both epoxide, catalyst, and CO_2 in the rate-determining step. The strong structure/activity correlation opens the route for the design of advanced catalysts. We plan to fully explore different aspects of this dependence including the introduction of chiral auxiliary and the construction of molecular cages around the P−H sites.[30]

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Catalytic procedures, protocol for the determination of isolated yield, ^{31}P NMR spectra of catalysts (**2a**−**2c**) before and after cycloaddition of CO_2 to styrene oxide after 7 h (1 mol %) and 96 h (0.1 mol %) of reaction, and kinetics analysis showing first-order dependence on epoxide, catalyst, and CO_2 concentrations. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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■ REFERENCES

(1) Song, C. *Catal. Today* **2006**, *115*, 2.
(2) Omae, I. *Catal. Today* **2006**, *115*, 33.
(3) Halmann, M. M. *Chemical Fixation of Carbon Dioxide: Methods for Recycling CO_2 into Useful Products*; CRC Press, Inc.: Boca Raton, 1993.
(4) Sakakura, T.; Choi, J.-C.; Yasuda, H. *Chem. Rev.* **2007**, *107*, 2365.
(5) Aresta, M., Ed. *Carbon Dioxide as Chemical Feedstock*; Wiley-VCH: Weinheim, 2010.
(6) Martin, R.; Kleij, A. W. *ChemSusChem* **2011**, *4*, 1259.
(7) Sakakura, T.; Choi, J.-C.; Yasuda, H. *Chem. Rev.* **2007**, *107*, 2365.

(8) Jessop, P.; Ikariya, T.; Noyori, R. *Chem. Rev.* **1995**, *95*, 259.
(9) North, M.; Pasquale, R.; Young, C. *Green Chem.* **2010**, *12*, 1514.
(10) Bruckmeier, C.; Rieger, B.; Herrmann, W. A.; Kühn, F. E. *Angew. Chem., Int. Ed.* **2011**, *50*, 8510.
(11) Darensbourg, D. J. *Chem. Rev.* **2007**, *107*, 2388.
(12) Schäffner, B.; Schäffner, F.; Verevkin, S. P.; Börner, A. *Chem. Rev.* **2010**, *110*, 4554.
(13) Shaikh, A. A. G.; Sivaram, S. *Chem. Rev.* **1996**, *96*, 951.
(14) Clements, J. H. *Ind. Eng. Chem. Res.* **2003**, *42*, 663.
(15) Du, Y.; Cai, F.; Kong, D. L.; He, L. N. *Green Chem.* **2005**, *7*, 518.
(16) Klaus, S.; Lehenmeier, M. W.; Anderson, C. E.; Rieger, B. *Coord. Chem. Rev.* **2011**, *255*, 1460.
(17) Darensbourg, D. J.; Holtcamp, M. W. *Coord. Chem. Rev.* **1996**, *153*, 155.
(18) Decortes, A.; Castilla, A. M.; Kleij, A. W. *Angew. Chem., Int. Ed.* **2010**, *49*, 9822.
(19) Kim, H. S.; Kim, J. J.; Lee, B. G.; Jung, O. S.; Jang, H. G.; Kang, S. O. *Angew. Chem., Int. Ed.* **2000**, *39*, 4096.
(20) Alvaro, M.; Baleizao, C.; Das, D.; Carbonell, E.; García, H. *J. Catal.* **2004**, *228*, 254.
(21) Kawanami, H.; Sasaki, A.; Matsui, K.; Ikushima, Y. *Chem. Commun.* **2003**, 896.
(22) He, L.-N.; Yasuda, H.; Sakakura, T. *Green Chem.* **2003**, *5*, 92.
(23) (a) Lensink, S. K. X.; Verkade, J. G. *J. Am. Chem. Soc.* **1989**, *111*, 3478. (b) Kisanga, P. B.; Verkade, J. G.; Schwesinger, R. *J. Org. Chem.* **2000**, *65*, 5431. For a review see: (c) Verkade, J. G.; Kisanga, P. *Tetrahedron* **2003**, *59*, 7819 and references therein. For more recent examples see: (d) Chintareddy, V. R.; Wadhwa, K.; Verkade, J. G. *J. Org. Chem.* **2009**, *74*, 8118. (e) Wadhwa, K.; Chintareddy, V. R.; Verkade, J. G. *J. Org. Chem.* **2009**, *74*, 6681. (f) Wadhwa, K.; Verkade, J. G. *J. Org. Chem.* **2009**, *74*, 5683. (g) Wadhwa, K.; Verkade, J. G. *J. Org. Chem.* **2009**, *74*, 4368. (h) Urgaonkar, S.; Verkade, J. G. *Org. Lett.* **2005**, *7*, 3319. (i) Su, W.; McLeod, D.; Verkade, J. G. *J. Org. Chem.* **2003**, *68*, 9499. (j) Raders, M. R.; Verkade, J. G. *J. Org. Chem.* **2010**, *75*, 5308. (k) Chintareddy, V. R.; Ellern, A.; Verkade, J. G. *J. Org. Chem.* **2010**, *75*, 7166.
(24) Verkade, J. G. *Five-Coordinate and Quasi-Five-Coordinate Phosphorus*; ACS Symposium Series 486; 1992; Chapter 5, p 64.
(25) (a) Maitlis, P. M.; Haynes, A.; James, B. R.; Catellani, M.; Chiusoli, G. P. *Dalton Trans.* **2004**, *21*, 3409. (b) More, P. G.; Dalave, N. V.; Lawand, A. S.; Nalawade, A. M. *J. Indian Chem. Soc.* **2007**, *84*, 394.
(26) Liu, X.; Verkade, J. G. *J. Org. Chem.* **1999**, *64*, 4840.
(27) Fetterly, B. M.; Jana, N. K.; Verkade, J. G. *Tetrahedron* **2006**, *62*, 440.
(28) Dimitrov-Raytchev, P.; Dutasta, J.-P.; Martinez, A. *ChemCatChem* **2012**, *4*, 2045.
(29) Kisanga, P. B.; Verkade, J. G. *Tetrahedron* **2001**, *57*, 467.
(30) Dimitrov-Raytchev, P.; Martinez, A.; Gornitzka, H.; Dutasta, J. P. *J. Am. Chem. Soc.* **2011**, *133*, 2157.
(31) (a) Oertel, G.; Malz, H.; Holtschmidt, H. *Chem. Ber.* **1964**, *97*, 891. (b) Jensen, K. A.; Dahl, O. *Acta Chem. Scand.* **1970**, *24*, 1179. (c) Pudovik, M. A.; Kibardina, L. K.; Aleksandrova, I. A.; Khairullin, V. K.; Pudovik, A. N. *Zh. Obshch. khim.* **1981**, *51*, 530.
(32) Yang, Z.-Z.; He, L.-N.; Miao, C.-X.; Chanfreau, S. *Adv. Synth. Catal.* **2010**, *352*, 2233.
(33) North, M.; Pasquale, R. *Angew. Chem., Int. Ed.* **2009**, *48*, 2946.