A Homogeneous Gallium(III) Compound Selectively Catalyzes the Epoxidation of Alkenes

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S Supporting Information

ABSTRACT: We demonstrate that a simple gallium(III) complex, $[Ga(phen)_2Cl_2]Cl$ (phen = 1,10-phenanthroline), can serve as a homogeneous catalyst for the epoxidation of alkenes. The olefin epoxidations proceed relatively quickly at mild temperatures and, under optimum conditions, are highly selective for the epoxide product.

Group 13 elements have been explored intensively as catalysts for many reactions because of their low cost and ability to be readily extracted and recovered from reaction mixtures.[1] The overwhelming majority of their catalytic capability derives from their strong Lewis acidity.[2−6] Alkyl and hydrido complexes with these elements are also well-known for their ability to stoichiometrically reduce various functional groups, with the metal complex donating a carbanion or hydride, respectively.[2,3,7−9] Because of the limited redox activity exhibited by these elements, there are comparatively few reports of group 13 catalyzed oxidation−reduction reactions; notable examples include Meerwein−Verley−Ponndorf carbonyl reduction and Oppenauer oxidation.[5,10−19] The hydrocarbon oxidation catalysis that has been reported tends to be unselective; the documented olefin epoxidation, for instance, is accompanied by substantial allylic oxidation.[12−17]

This Communication reports the selective epoxidation of olefins by the previously described $[Ga(phen)_2Cl_2]Cl$ (phen = 1,10-phenanthroline).[20−22] To the best of our knowledge, this is the first instance of a gallium(III) compound serving as a homogeneous catalyst in alkene epoxidation (Scheme 1), although this metal ion has previously been a component in heterogeneous catalysts for such reactions.[14,17]

Scheme 1
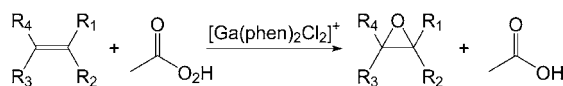
The $[Ga(phen)_2Cl_2]Cl$ complex was crystallized from ethanol (Figure 1). The structural data confirm the compositions of the inner and outer spheres, with the outer-sphere chloride located 5.57 Å away from the Ga^{III} ion. The halides are terminal rather than bridging, analogous to what is observed in the structure of $[Ga(phen)_2Br_2]Br$.[23] The structure is a rare example of a hexacoordinate dihalide gallium(III) complex.[23−25] The chlorides are cis to each other, as has been

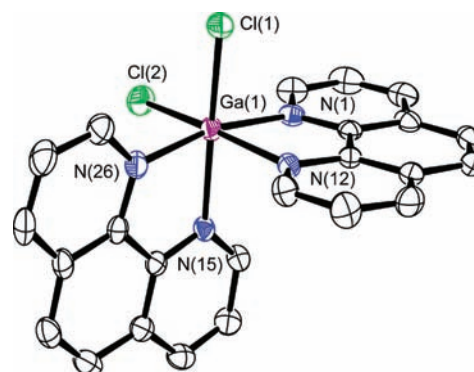**Figure 1.** ORTEP representation of the cation $[Ga(phen)_2Cl_2]^+$. The counterion, H atoms, and outer-sphere solvent molecules have been removed for clarity. All thermal ellipsoids are drawn at 50% probability. A fuller description of the structure, including a table of metrical parameters, is located in the Supporting Information.

observed in other hexacoordinate dihalide gallium(III) complexes with bidentate ligands.[23−25]

The ability of $[Ga(phen)_2Cl_2]Cl$ to catalyze the epoxidation of alkenes in acetonitrile (MeCN) was initially tested using H_2O_2. Although H_2O_2 served as a competent terminal oxidant in aluminum(III)-catalyzed alkene epoxidation,[12,15] it did not lead to any epoxidation with the gallium(III) catalyst. Speculating that the poor binding affinity of H_2O_2 to Ga^{III} was responsible for the lack of activity,[26] we investigated two grades of peracetic acid (PAA). In addition to commercially available PAA (PAA_C, pH ∼ 1), we prepared and investigated a less acidic, custom-made grade (PAA_R, pH ∼ 4)[27] that previously led to excellent activity in manganese-catalyzed epoxidation.[28,29] PAA_R was prepared by reacting acetic acid and H_2O_2 in the presence of a highly acidic resin (Amberlite IR-120); PAA_R lacks the ∼1% H_2SO_4 additive that is used as the catalyst for the commercial preparation of PAA. The peracids should ligate metal ions more readily than H_2O_2, particularly under more basic conditions.

Using PAA_C as the terminal oxidant led to modest epoxidation at 0 °C, but PAA_R was much more effective, particularly with electron-deficient substrates (Table 1). As is commonly observed, the more electron-deficient olefins tend to react less readily. The two substrates with two alkene groups, ethyl sorbate and 4-vinylcyclohexene, are oxidized exclusively at the more electron-rich site. These results parallel those found

Table 1. Yields/Turnover Numbers of Gallium(III)-Catalyzed Alkene Epoxidation Reactions by Various Grades and Amounts of PAA[a]

Substrate	Product	2 equiv PAAc[b]	2 equiv PAAR[b]	1 equiv PAAR[b]
(cyclohexene)	(cyclohexene oxide)	17 (±4)	46 (±8)[c]	31 (±4)
(cyclooctene)	(cyclooctene oxide)	40 (±3)	87 (±4)[c]	64 (±4)
(styrene)	(styrene oxide)	0	11 (±2)	8 (±2)
(1-octene)	(1-octene oxide)	15 (±4)	41 (±3)[c]	30 (±3)
(ethyl sorbate)	(epoxide)	0	11 (±2)	8 (±2)
(vinylcyclohexene)	(epoxide)	33 (±8)	61 (±6)	48 (±5)

[a]Standard reaction conditions: MeCN, 0 °C, initial concentrations of 5.0 mM [Ga(phen)$_2$Cl$_2$]Cl and 500 mM alkene. The yields, defined as the percentage of alkene converted to the epoxide, were measured at 1 h via gas chromatography. The yields also serve as the turnover numbers because the substrate is present in a 100-fold excess relative to the gallium(III). [b]The ratio of [Ga(phen)$_2$Cl$_2$]Cl/alkene/PAA was 1:100:200 when 2 equiv of PAA was used and 1:100:100 when 1 equiv of terminal oxidant was added. [c]Isolated yields for cyclohexene oxide (39%), cyclooctene oxide (77%), and 1-octene oxide (37%) are reported in the Supporting Information.

for the aforementioned manganese(II)-catalyzed alkene epoxidation.[28,29] Although the yields of the epoxide do increase when more PAA$_R$ is added, the reactions become noticeably less efficient. Adding one additional equiv of PAA$_R$ to the cyclooctene reaction, for instance, only raises the yield of the epoxide from 64% to 87%, with a concomitant drop in the oxidative efficiency from 64% to 44%.

The control studies confirm that both the phen ligands and the Ga^{III} ions are essential for the observed catalysis. GaCl$_3$ by itself does not catalyze epoxidation to an appreciably greater extent than the metal-free controls (Table S3 in the Supporting Information). We hypothesize that the electron-withdrawing nature of the phen ligands[30] amplifies the Lewis acidity of the Ga^{III} metal center relative to that in the chloride salt.

In order to exclude the mechanistic possibility of a highly active transition-metal contaminant, we assessed the catalytic activity of 0.1 mM [Mn(phen)$_2$Cl$_2$] and found it to be inferior to that of 5.0 mM [Ga(phen)$_2$Cl$_2$]$^+$. The loading of the manganese(II) complex, which is known to catalyze olefin epoxidation,[29] is meant to mimic an active 2% molar impurity. The 2% value is a conservative upper limit, given the high purities of the available gallium(III) salts and the crystallinity of the [Ga(phen)$_2$Cl$_2$]$^+$ catalyst (Figure 1). The purity of the gallium(III) complex is further confirmed by inductively coupled plasma optical emission spectrometry (ICP-OES), which found that the iron and manganese contents were equal within error to those of a blank sample. That the reactivity cannot be fully accounted for by a highly active transition-metal contaminant demonstrates that a gallium(III) species is indeed catalyzing olefin epoxidation.

Monitoring the yield of several epoxidation reactions over time reveals that the reactivity persists for approximately 2 h at 0 °C (Figure 2). Mass spectrometric (MS) analysis of the
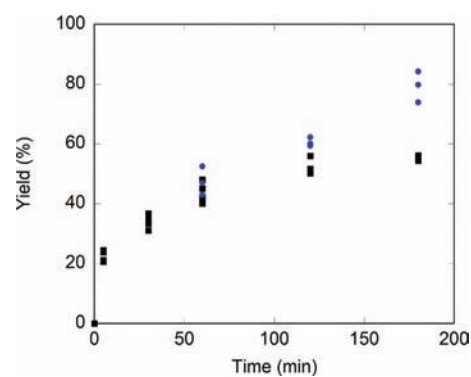

Figure 2. Yield of cyclohexene oxidation by 2 equiv of PAA$_R$ as a function of time. The blue data points correspond to the reactivity observed in the presence of 10 equiv of additional phen. Otherwise, the reaction conditions are identical with those in Table 1.

reaction suggests that the chloride ligands are displaced by acetate almost immediately; by mass balance, this would generate HCl. MS analysis also reveals that the phen ligands dissociate from the Ga^{III} ions over the period of the reaction, with noticeably fewer Ga^{III}phen adducts remaining at 1 h. Because the gallium(III) salts by themselves are not competent catalysts for olefin epoxidation, dissociation of the phen ligands is a plausible explanation for the loss of activity. Displacement of the phen ligand from the metal is likely a consequence of the increasing acidity of the solution; during the reactions, PAA (pK_a = 8.2) is ultimately reduced to the more acidic acetic acid (pK_a = 4.8). The resultant greater concentration of H$^+$ will more effectively compete with the Ga^{III} ions for the N-donor atoms of the phen ligands. This explanation is also consistent with the higher epoxide yields for the reactions using the less acidic PAA$_R$. The lifetime of the catalytic activity and the ultimate yield of the epoxide can be increased by adding free phen ligand to the initial reaction mixture (Figure 2). With the shown cyclohexene epoxidation, the yield at 3 h increased from 55% to 79% when 10 equiv of additional phen were present. Attempts to further increase the yield by running the reaction in a solution of 50 mM HEPES in H$_2$O buffered to pH 7.0 were unsuccessful. The yield measured at 3 h was 68% in the HEPES buffer, as opposed to 79% in MeCN. We attribute this lesser activity to the immiscibility of the alkene substrate with water.

The [Ga(phen)$_2$Cl$_2$]$^+$/PAA mixtures oxidize olefins quickly relative to other group 13 metal-containing systems. Previously reported homogeneous and heterogeneous aluminum(III) and gallium(III) catalysts for these reactions have been reported to turn over up to ~50 times.[13−15,17] The most successful of these alkene epoxidations were run at a relatively high temperature (80 °C) and required 4−5 h to reach this level of activity.[14,15] In contrast, the turnover number of 87 for the best cyclooctene epoxidation in Table 1 was measured at 1 h and corresponded to reactions run at 0 °C. Increasing the reaction temperature to 25 °C did not have a substantial impact on the yield. When cyclohexene epoxidation (MeCN, 10 equiv of additional phen) was run at this temperature, the yield at 3 h only increased from 79% to 82%. Although the time and temperature required for the reactions are both lower than those reported for other group 13 mediated epoxidations, it should be noted that the gallium(III)-promoted epoxidations proceed much more slowly than those catalyzed by Mn^{II}phen complexes and other transition-metal compounds.[28,29,31,32]

Notably, the only oxidized organic products with the 1% catalyst loading are epoxides. This again contrasts with other reported group 13 catalyzed alkene epoxidations, which produce sizable amounts of alcohols and ketones/aldehydes.[12−15] This selectivity is lost as the catalyst loading is lowered. With a gallium(III) loading of 0.1%, the major products are 3-cyclohexenol (39%) and 1,2-cyclohexanediol (51%); the yield of cyclohexene oxide is only 8%. The new products do not result from further chemical transformation of the epoxide; epoxides do not react with the Ga^{III}/PAA mixtures when used as substrates. The inability of the system to oxidize epoxides suggests that different oxidation mechanisms, as opposed to overoxidation, occur with the higher PAA/Ga^{III} ratio.

On the basis of our observations, we speculate that the olefin epoxidation proceeds through a Sharpless-type mechanism (Scheme 2),[33] as has been proposed for a $[Al(H_2O)_6]^{3+}/H_2O_2$

Scheme 2
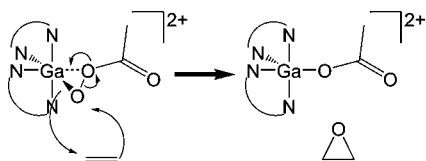
system.[12] The competitive C−H activation observed in the aluminum(III) system was attributed to the formation of $[Al(H_2O)_4(H_2O_2)(O_2H)]^{2+}$ species.[12] The bidenticity of the phen ligands would be anticipated to hinder similar chemistry in the $[Ga(phen)_2Cl_2]^+$ reactions by better blocking the coordination of a second equiv of terminal oxidant. When the concentration of PAA is much higher, the formation of such species should be more likely. The higher levels of 2:1 PAA/Ga^{III} adducts associated with the 0.1% catalyst loading would account for the observed allylic oxidation.

In summary, we report the first homogeneous gallium(III) catalyst for olefin epoxidation. Relative to other group 13 catalysts, the activity of $[Ga(phen)_2Cl_2]^+$ is both fast and, with a 1% catalyst loading, exquisitely selective for the epoxide product. We attribute the greater activity and selectivity to the presence of the electron-withdrawing and bidentate 1,10-phenanthroline ligands. Although Ga^{III} is widely perceived to be less Lewis acidic than Al^{III}, the greater affinity of Ga^{III} for these π-accepting N-donor ligands compensates for this deficiency. The results suggest that the full potential of group 13 metals for hydrocarbon oxidation reactions has not yet been realized, and the $[Ga(phen)_2Cl_2]^+$ complex may be a promising lead to other homogeneous, non-transition-metal catalysts.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information
X-ray crystallographic data in CIF format, experimental section, isolated yields, full crystallographic data for $[Ga(phen)_2Cl_2]Cl$, ICP-OES data, control studies, yield of cyclooctene epoxidation as a function of time, MS analysis of cyclooctene epoxidation at 5 s and 60 min, and a summary of alkene epoxidation catalyzed by a lower loading of $[Ga(phen)_2Cl_2]Cl$. 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.

■ ACKNOWLEDGMENTS

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