Erbium(III) Triflate: A Valuable Catalyst for the Rearrangement of Epoxides to Aldehydes and Ketones

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Abstract: Rearrangement of epoxides is performed with erbium triflate as catalyst. In contrast to most proposed catalysts for this reaction, erbium triflate works well with both aromatic and aliphatic epoxides.

Key words: catalysis, epoxides, Erbium triflate, Lewis acid, rearrangements

The rearrangement of epoxides to carbonyl compounds is a useful synthetic transformation and hence several reagents have been utilized for this purpose.[1] It has been performed under acid and base catalysis, and mechanistic aspects including the migratory aptitudes of different groups attached to the epoxy carbon have been explored in detail.[2] Nevertheless, despite the number of methods that have been developed, only few are both regioselective and catalytic. Further, most literature methods do not work well for the rearrangement of aliphatic epoxides unless they are di- or tri-substituted.

In the course of our research program on Lewis acid-catalyzed reactions, we found that the hydrates of cerium and erbium triflate are very useful and environmentally friendly catalysts for many acid-catalyzed reactions.[3]

Moreover, it is possible to rule out that the triflic acid could be the active catalyst, in fact the solutions of $Ce(OTf)_3$ and $Er(OTf)_3$ in water are only weakly acidic (pH = 6.0, pH = 5.9, respectively), and the aqueous layers from the workups were even less acidic (pH = 6.7).

We now wish to report that erbium triflate is a highly efficient and regioselective catalyst for the rearrangement of epoxides to carbonyl compounds.

At first, the reactivity of cerium and erbium triflate was compared by studying their effect on the rearrangement of styrene oxide (**1a**) to phenylacetaldehyde (**2a**, Table 1).

Cerium triflate was a less efficient catalyst than erbium, since reaction times are longer, except when acetonitrile was used as solvent. Moreover, it should be noted that erbium salt can be used without drying either the salt or the solvent while diols are formed in the presence of cerium salts in wet solvents.[4]

Table 1 Comparison between Hydrate Cerium and Erbium Triflate as Catalyst for Rearrangement of the Styrene Oxide (**1a**) to Phenylacetaldehyde (**2a**) at Room Temperature

Entry	Catalyst (mol%)	Solvent	Time	Yield (%)
1	$Ce(OTf)_3$ (1)	CH_3NO_2	29 h	80
2	$Er(OTf)_3$ (1)	CH_3NO_2	24 h	81
3	$Ce(OTf)_3$ (1)	MeCN	12 h	100
4	$Er(OTf)_3$ (1)	MeCN	24 h	79
5	$Ce(OTf)_3$ (1)	THF	12 h	42
6	$Er(OTf)_3$ (1)	THF	100 min	63
7	$Ce(OTf)_3$ (1)	Et_2O	3 h	100
8	$Er(OTf)_3$ (1)	Et_2O	90 min	100
9	$Ce(OTf)_3$ (1)	CH_2Cl_2	40 min	100
10	$Er(OTf)_3$ (1)	CH_2Cl_2	20 min	100
11	$Ce(OTf)_3$ (1)	CH_2Cl_2	4 h	100
12	$Er(OTf)_3$ (1)	CH_2Cl_2	45 min	100

[a] GC yields.

Erbium triflate is an efficient catalyst especially in nonpolar solvents, where the coordination with the oxygen of the epoxides increases. In fact, the best results (fast reaction times and high yields) were obtained in less polar solvents such as dichloromethane (Table 1, entry 7).

Remarkably, both catalysts perform the rearrangement with catalyst percentages as little as 0.1% mol (Table 1, entries 11 and 12). They did not work so well when other substrates, less reactive than styrene oxide, were used. Thus, the use of 1% mol of catalyst was the best compromise.

Based on the best results presented in Table 1, the rearrangement of a series of epoxides was studied (Table 2).[5] The reactions were very clean and further purification was unnecessary for all the tested compounds except limonene (**1f**), where some unidentified by-products were found. In agreement with the literature,[2] rearrangements of alkyl epoxides were more difficult than aryl ones, so refluxing temperatures were necessary for the reaction to occur.

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This is a good example of green chemistry since this method shows atom economy, no requirement of purification processes, and an easily recoverable, non-toxic catalyst.[6]

One of the best procedures reported to perform this rearrangement employs bismuth salts,[2a,b] which is restricted to aryl epoxides and to aliphatic epoxides with a tertiary center only. The present procedure has comparable yields, ratios, and catalyst percentages, but allows rearrangement of mono-substituted aliphatic epoxides.

It is accepted that the direction of ring-opening of the epoxide is governed by two main factors: the direction of the ring-opening and the relative migratory aptitude of the substituents.[2c] After coordination of the Lewis acid to the oxygen atom, the torsional energy is released through the formation of the most stable carbocation.

The highest electron-releasing power of aryl groups causes invariably that aryl mono-substituted epoxides rearrange to the products in which carbonyl is far from the phenyl ring (Table 2, entries 1–3). Mono-alkyl substituted epoxides preferentially give the most substituted carbocation, with subsequent 1,2-hydride shift to afford aldehydes (Table 2, entries 9–11), in comparable ratio and yield with the best reported method, which employs much more complex and expensive metalloporphyrin catalysts.[2d]

Table 2 Rearrangement of Epoxides in the Presence of 1 mol% of Er(OTf)$_3$ in Dichloromethane at Room Temperature (unless otherwise noted)

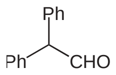
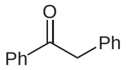
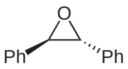
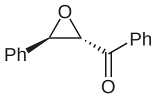
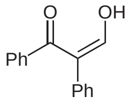
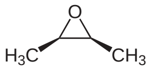
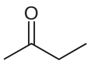
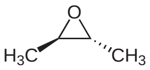
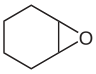
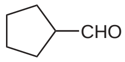
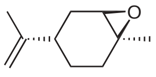
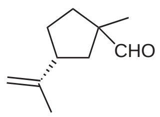
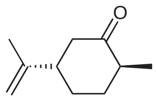
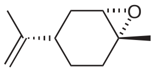
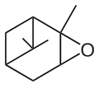
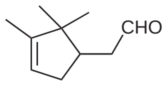
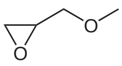
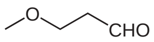
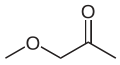
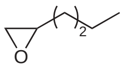
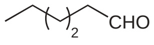
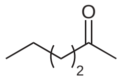
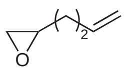
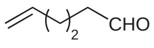
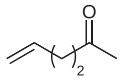
Entry	Epoxide	Time	Product	Yield (%) (**2/3**)[c]
1	 *cis*-**1b**	20 min	 **2b**  **3b**	99 (81/19)
2	 *trans*-**1b**	45 min	**2b**	>99
3	 1c	2.5 h	 **2c**	>99[7]
4	 *cis*-**1d**	3 h	 **3d**	50[b]
5	 *trans*-**1d**	3 h	**3d**	53[b]

Table 2 Rearrangement of Epoxides in the Presence of 1 mol% of Er(OTf)$_3$ in Dichloromethane at Room Temperature (unless otherwise noted) (continued)

Entry	Epoxide	Time	Product	Yield (%) (**2/3**)[c]
6	 **1e**	5 h[a]	 **2e**	>99
7	 *trans*-**1f**	3 h	 **2f**  **3f**	82 (14/86)[8,9]
8	 *cis*-**1f**	2.5 h	**2f, 3f**	87 (20/80)[8,9]
9	 **1g**	1 h	 **2g**	83[10]
10	 **1h**	4 h[a]	 **2h**  **3h**	>99 (97/3)[11]
11	 **1i**	13 h[a]	 **2i**  **3i**	>99 (95/5)
12	 **1j**	14 h[a]	 **2j**  **3j**	>99 (93/7)[12]

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[a] These reactions were carried out at reflux temperatures.

[b] Reaction carried out in a sealed vial. Aldehyde was never detected. An unidentified carbonyl compound was responsible of the other 50% of the reaction.

[c] All compounds gave satisfactory microanalyses, and their spectroscopic data were compared with literature (cited) or with true sample (empty cells).

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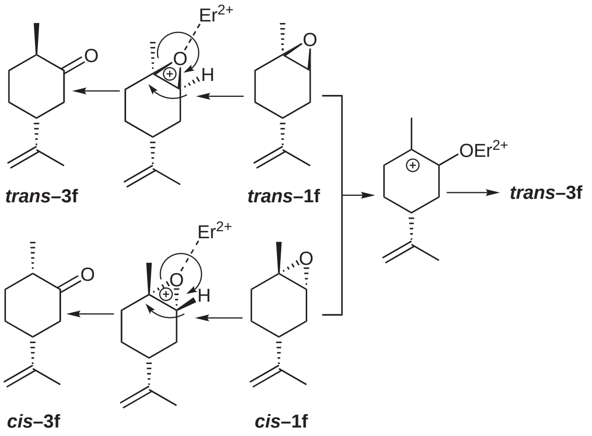
The formation of a carbocation intermediate is also supported by the rearrangement of limonene oxide. Both isomers led to similar mixtures of the rearranged products. Moreover, both ^{13}C NMR and ^{1}H NMR spectra of the ketones arising from the two reactions are super-imposable and in agreement with formation of *trans*-**3f**.[13] If the rearrangement is a concerted process, two isomers should be obtained (Scheme 1).



Scheme 1

The rearrangement α-pinene oxide leads to campholenic aldehyde **2g** (Table 2, entry 8), the key intermediate in the synthesis of naturanol,[14] in very high yields (only less than 10% of carveol was detected by GC/MS).

In conclusion, erbium triflate is a very useful catalyst for the rearrangement of epoxides to carbonyl compounds. The advantages of this catalyst include the observed regioselectivity, the broad applicability and easy recoverability.

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(4) For example, in bench-top MeCN after 48 h, only 38% yield of **2a** was detected with Ce(OTf)$_3$, with phenylethanediol as the major product (57%).

(5) **Typical Procedure:** A solution of the epoxide (1 mmol) in CH$_2$Cl$_2$ (3 mL) was stirred at r.t. as Er(OTf)$_3$ (1 μmol) was added. Rearrangements of aliphatic epoxides were carried out under reflux conditions. The reaction was monitored by GC/MS. At the time reported in Table 2, the starting material was completely consumed. The reaction was poured into H$_2$O, extracted twice with CH$_2$Cl$_2$, dried over Na$_2$SO$_4$ and evaporated under reduced pressure. Both NMR and elemental analyses of the residue showed the products to be >98% pure. Only limonene and α-pinene oxides required purification by preparative TLC (eluent CHCl$_3$–MeOH, 9:1).

(6) After reaction workup, the aqueous phase can be evaporated under reduced pressure to furnish the erbium salt in 90% recovered yield, as a pale pink solid. After drying over P$_2$O$_5$ overnight, the recovered catalyst was reused five times in the rearrangement of **1a**, with recovered yields of **2a** always over 90%.

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(13) Spectra of both **3f** isomers are known[9] and they are slightly different (e.g. double-bond carbons are found at $\delta = 147.6$, 109.6 ppm and $\delta = 146.75$, 111.42 ppm and the vinyl protons at $\delta = 4.76$, 4.73 and 4.83, 4.70 ppm in *trans*-**3f** and *cis*-**3f**, respectively).

(14) Naturanol is a natural product of great importance in the perfume industry.

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