Solid-Acid Catalysed Rearrangement of Cyclic α,β-Epoxy Ketones

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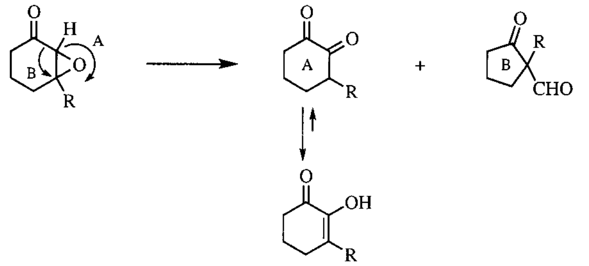
Various cyclic α,β-epoxy ketones rearranged to α-formyl ketones and/or *vic*-diones in the presence of catalytic amounts of zeolites and montmorillonite K10. This provides an excellent alternative to conventional homogeneous systems with respect to yields and workup. Differences in product distribution and type of products in the rearrangement of pulegone oxide could be reasonably explained by invoking different pathways for homogeneous and heterogeneous catalysts.

Introduction

α,β-Epoxy ketones are interesting intermediates in organic synthesis. They not only undergo the usual reactions of epoxides,[1] but are also susceptible to several useful reactions owing to the presence of a carbonyl group.[2] Cyclic α,β-epoxy ketones, which are readily available from the appropriate α,β-unsaturated ketones by epoxidation with an alkaline solution of a hydroperoxide, are easily converted into aldehydes and diones upon treatment with an acid. In the presence of a Lewis acid they cleave at the β-carbon atom as depicted in Scheme 1.[3]



Scheme 1. Lewis acid catalysed rearrangement of a cyclic α,β-epoxy ketone

Cleavage at the α-carbon atom is energetically unfavourable since this generates partial positive charges on adjacent atoms.[4] Cleavage is followed by hydrogen migration (route A) or acyl migration (route B). Acyl migration results in ring contraction and is favoured over hydrogen migration when $BF_3{\cdot}Et_2O$ is used as a catalyst, particularly if an additional substituent is present at the β-position.[3,5,6] Conversely, 1,2-diones were found to be the major products upon treatment of cyclic α,β-epoxy ketones with aqueous solutions of hydrochloric acid[7] or sulfuric acid.[8] Probably, hydrolysis of the epoxide to its corresponding diol precedes the actual rearrangement under these conditions.

Several products resulting from rearrangement of cyclic α,β-epoxy ketones are of significant synthetic interest. Various 1,2-diones, for example, are widely used as food flavours,[9] and $BF_3{\cdot}Et_2O$-mediated rearrangement of optically active cyclic α,β-epoxy ketones was a key step in the asymmetric synthesis of (−)-frontalin (a pheromone) and (+)-malyngolide (an antibiotic).[10]

Although they are attractive from the viewpoint of ease of recovery and recycling, heterogeneous catalysts have scarcely been used in the rearrangement of α,β-epoxy ketones. Ho and Liu used an aqueous suspension of an ion-exchange resin (H^+ form) in the rearrangement of 2,3-epoxy-3-methylcyclopentanone.[9] Rao and Rao reported the rearrangement of highly active chalcone oxides to 1,3-diphenylpropane-1,2-diones at room temperature when silica gel was used as a catalyst.[11] Zeolites have been used in the industrially important rearrangement of phenyl glycidic acid esters, which are structurally closely related to acyclic α,β-epoxy ketones, to phenyl α-keto carboxylic acid esters.[12,13]

We have investigated the rearrangement of various cyclic α,β-epoxy ketones with the use of solid (Brønsted) acids extensively, and in this paper we will show that, because of the excellent yields and the facile workup, it provides an excellent alternative to the classical homogeneous system with $BF_3{\cdot}Et_2O$.

Results and Discussion

Rearrangement of Isophorone Oxide

We chose isophorone oxide as a model compound, which is easily made from the cheap isophorone. Rearrangement of isophorone oxide (**1**) with $BF_3{\cdot}Et_2O$ or the heterogeneous catalysts gave, as major products, 3,5,5-trimethyl-1,2-cyclohexanedione (**2**) and 1,4,4-trimethyl-2-oxocyclopentane-1-carbaldehyde (**3**) (Scheme 2). The results of the reaction with the various catalysts are shown in Table 1.

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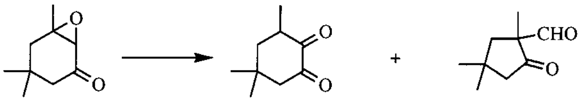


1 **2** **3**

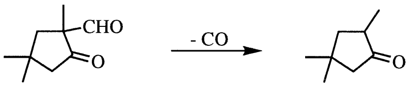
Scheme 2. Rearrangement of isophorone oxide (**1**) to 3,5,5-trimethyl-1,2-cyclohexanedione (**2**) and 1,4,4-trimethyl-2-oxocyclopentane-1-carbaldehyde (**3**)

Table 1. Conversion of isophorone oxide (**1**) and selectivities to 3,5,5-trimethyl-1,2-cyclohexanedione (**2**), 1,4,4-trimethyl-2-oxocyclopentane-1-carbaldehyde (**3**) and 2,4,4-trimethylcyclopentanone (**4**)

Catalyst	Solvent[a]	Temp. (°C)	Time (min)	Conv. (%)	Selectivity (%)			Ratio (**3**+**4**/**2**)
					2	**3**	**4**	
None	B	80	120	0	0	0	0	-
$BF_3 \cdot Et_2O$	B	rT	10	100	2	76	0	36
Silica gel	B	80	120	3	0	0	0	-
H-ZSM-5	CB	132	120	6	5	71	0	16
Na-Mor	B	80	1200	26	14	63	0	4.5
H-Mor	B	80	120	100	8	81	0	10
H-Mor	B	80	1320	100	13	81	0	6.2
H-Mor	CB	80	120	98	9	80	1	9.3
H-Mor	CB	132	120	100	13	81	1	6.4
H-Mor[b]	B	80	120	30	4	80	1	22
H-Mor[c]	B	80	120	100	5	85	1	18
H-Mor[d]	B	80	120	59	3	78	0	27
H-Mor[d]	B	80	1500	99	10	78	0	8.2
H-beta	B	80	120	100	15	56	25	5.6
H-beta	CH	81	120	100	16	59	15	4.6
H-beta[b]	B	80	120	100	11	71	9	7.2
NaHY	B	80	120	63	18	67	1	3.7
NaHY	B	80	1380	97	21	69	1	3.3
NaHY	CB	132	120	100	29	58	7	2.2
Mont.K10	B	RT	1350	40	10	63	0	6.3
Mont.K10	B	80	120	100	14	78	0	5.5
Mont.K10	CB	132	120	100	16	78	2	4.9

[a] B = Benzene, CB = chlorobenzene and CH = cyclohexane. – [b] Poisoned with triphenylphosphane. – [c] Dealuminated. – [d] Silylated.

No reaction was observed in the absence of catalyst. The low conversion observed with silica gel is presumably due to adsorption of a small amount of **1** on the catalyst, since the GC analyses were based only on the liquid phase of the reaction mixture. In most cases, 2,4,4-trimethylcyclopentanone (**4**) was also observed as a product. The formation of **4** can be explained by deformylation of **3** as depicted in Scheme 3. Deformylation of **3** can also be effected by treatment with an aqueous sodium hydroxide solution.[14] Product **2** can be separated simultaneously, because this α-diketone is alkali-soluble.



3 **4**

Scheme 3. Deformylation of 1,4,4-trimethyl-2-oxocyclopentane-1-carbaldehyde (**3**) to 2,4,4-trimethylcyclopentanone (**4**)

Table 1 shows that the acidic form of the zeolites, with the exception of H-ZSM-5, and montmorillonite K10 were able to rearrange **1** to **2** and **3** with high conversions and selectivities. The total selectivities to **2** and **3** ranged from 70 to 94% and are therefore comparable to or even better than those found for the homogeneously catalysed reaction with $BF_3 \cdot Et_2O$ (Table 1).

H-mordenite-, H-beta- and montmorillonite-catalysed rapid rearrangement of **1** in refluxing benzene, led, for example, to complete conversion in 15 min with H-beta. Substantial deformylation was observed, however. Since **3** is the precursor of **4**, the total (initial) selectivity to **2** and **3**, defined as the sum of the selectivities to **2**, **3** and **4**, was the highest for H-beta (96%). Replacement of benzene by the less polar cyclohexane in the reaction with H-beta partially suppressed the deformylation. In contrast, montmorillonite gave little deformylation in chlorobenzene, despite the fact that this catalyst had high activity (conversion 100% after 15 min) and was used at high temperature. Similarly, no deformylation was observed with montmorillonite in refluxing benzene, despite the high activity (nearly 100% conversion after 15 min). The observed lack of reaction of **1** in benzene at room temperature in the presence of this clay further showed that heating is necessary to establish effective rearrangement of **1**.

Replacement of benzene by the more polar chlorobenzene in the H-mordenite-catalysed rearrangement afforded a slower reaction rate at the same temperature. The use of refluxing chlorobenzene (b.p. 132 °C) instead of refluxing benzene afforded, with H-mordenite, a different product distribution after the same reaction time but after prolonged refluxing in benzene the final product distribution was similar.

Turnover numbers (defined as the molar ratio between rearranged epoxide and bulk aluminium) of up to 20 were found, but since they are a result of the choice of the reaction conditions they are probably amenable to further improvement.

Remarkably, all heterogeneous catalysts showed a lower ratio (**3**+**4**)/**2** than that observed with $BF_3 \cdot Et_2O$. The differences in the ratios (**3**+**4**)/**2** of the reactions performed with H-mordenite, H-beta and montmorillonite in refluxing benzene, on the other hand, were small. The results for H-mordenite in refluxing benzene show that this ratio can change when the reaction is prolonged beyond 100% conversion. This is probably due to a slower desorption rate of **2** from the catalyst than with **3** and **4** since prolongation of the reaction increased the selectivity to **2**, while the selectivities to **3** and **4** remained unchanged. In general, comparison of selectivities of various catalysts should be based on the same conversions. Moreover, as mentioned above, the GC analyses were based only on the liquid phase of the reaction mixture, and, owing to the relatively large amount of catalyst used with respect to substrate (30 wt%), significant quantities of product can be adsorbed on the catalyst. For these reasons, comparison of the ratios (**3**+**4**)/**2** is meaningful only when there is a large difference.

When zeolite NaHY was used as the catalyst, a relatively large amount of **2** was formed, but **3** was still the major product. This relatively high selectivity towards the dione was also observed for other cyclic α,β-epoxy ketones, thereby affording a convenient synthesis of various 1,2-diones, albeit in moderate yields. The reason for this special property of zeolite NaHY is not yet clear. The larger pore size might play a role. Moreover, zeolite NaHY is less acidic than H-mordenite, H-beta and montmorillonite, resulting in a weaker interaction with the substrate and/or products and a more facile desorption of **2**.

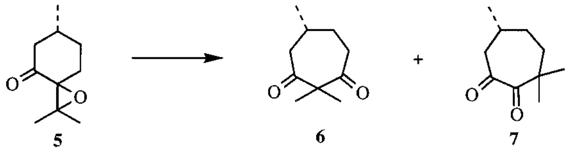
Because the outer surface of zeolites may contribute to their reactivity,[15] we investigated the effect of some outer surface treatments on the product distribution in the rearrangement of **1**. It was previously shown that treatment of H-mordenite[15] and H-beta[16] with triphenylphosphane and H-mordenite with tetraethyl orthosilicate[16] resulted in total deactivation of the outer surface activity. Dealumination of mordenite by treatment with nitric acid reduced the outer surface activity to approximately 7% of the original activity, without loss of the activity of the inner-pore system.[15]

Triphenylphosphane-poisoned H-beta gave the same conversion after 120 min as that observed for untreated H-beta; this is consistent with the notion that the reaction takes place in the micropores. A significant decrease in the formation of **4** by deformylation was observed, suggesting that deformylation takes place primarily on the outer surface.

Dealuminated mordenite showed the same conversion after 120 min as that found with untreated H-mordenite. In this case, it should be noted that dealumination of mordenite has a significant, but minor effect on the ratio (**3**+**4**)/**2**, because the total selectivities are nearly the same. Silylated mordenite showed a much lower reaction rate than untreated H-mordenite. Initially, the ratio (**3**+**4**)/**2** was higher, but it decreased significantly when the reflux time was prolonged. This experiment with silylated mordenite illustrates clearly the slow desorption of product **2** as mentioned above.

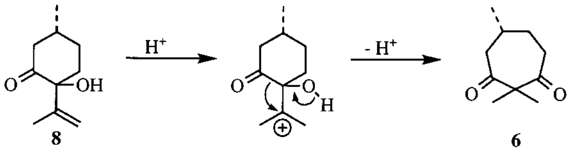
Rearrangement of Pulegone Oxide

Analogously to the rearrangement of isophorone oxide, epoxide ring opening of pulegone oxide (**5**) is expected to preferentially occur at the β-carbon atom; this is further facilitated by the presence of two methyl groups (tertiary carbon atom). Subsequent acyl or alkyl migration will result in the formation of 2,2,5-trimethylcycloheptane-1,3-dione (**6**) or 3,3,6-trimethylcycloheptane-1,2-dione (**7**), respectively (see Scheme 4).



Scheme 4. Expected rearrangement pathway of pulegone oxide (**5**) to 2,2,5-trimethylcycloheptane-1,3-dione (**6**) and 3,3,6-trimethylcycloheptane-1,2-dione (**7**)

Indeed, when a diastereomeric mixture of pulegone oxide (*cis*/*trans* = 1.7) was refluxed in benzene in the presence of various solid acids, 1,3-dione **6** was obtained as the major product. However, instead of the expected 1,2-dione **7**, 2-hydroxy-2-isopropenyl-5-methylcyclohexanone (**8**, for structure see Scheme 5) was formed as the other major product. Table 2 shows that the formation of both products (**6** and **8**) proceeded with excellent conversions and total selectivities.



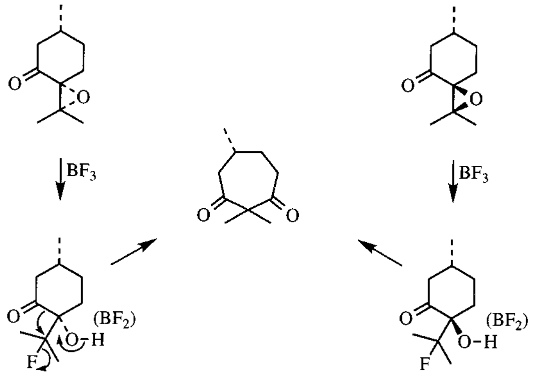
Scheme 5. Acid-catalysed conversion of 2-hydroxy-2-isopropenyl-5-methylcyclohexanone (**8**) to 2,2,5-trimethylcycloheptane-1,3-dione (**6**)

Table 2. Solid-acid catalysed rearrangement of pulegone oxide (**5**)

Catalyst	Time (min)	Conv.[a] (%)	Selectivity (%) **6**	**8**	Ratio **6/8**
NaHY	1200	97	67	29	2.3
HM	240	98	70	22	3.2
H-beta	15	100	70	15	4.8
H-beta	120	100	78	6	12
Montmorillonite K10	120	100	62	22	2.8

[a] Performed in refluxing benzene.

In striking contrast, homogeneous rearrangement of **5** with $BF_3 \cdot Et_2O$ in refluxing benzene gave **6** in an isolated yield of 92%.[5] In this case, it was shown[5] that the reaction proceeds via fluorohydrin intermediates (see Scheme 6). Since the flexible fluorohydrins could readily achieve the required conformation for concerted 1,2-acyl rearrangement, both diastereomers of pulegone oxide resulted in the formation of **6** as the sole product.



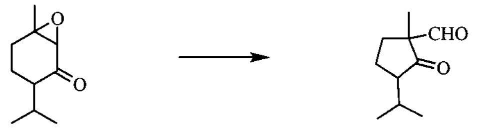
Scheme 6. Fluorohydrins in the $BF_3 \cdot Et_2O$-catalysed rearrangement of **5**[5]

Since involvement of fluorohydrin-like intermediates is precluded with the heterogeneous catalysts, rearrangement of pulegone oxide induced by solid acids will, therefore, probably occur via an unfavourable transition state. In such cases, the rate of substituent migration is probably much faster than the rate of rotation to an optimal conformation, and the result is therefore likely to be a divergent package of products.

Table 2 shows that when the reaction with H-beta (after 100% conversion) was prolonged, the selectivity to **8** slowly decreased in favour of **6**, a tendency that was also found, to a lesser degree, for the other solids. A possible explanation for this phenomenon is depicted in Scheme 5. Protonation of allylic alcohol **8** by the solid acid may result in a similar reaction intermediate to that formed in the rearrangement of pulegone oxide (((**5**) to 1,3-dione **6**, enabling the latter product to be formed also in an indirect way. Such a formation of **6** from **8** implies that the 1,3-dione is the thermodynamically more stable product. The slower conversion of **8** compared with **5** can be explained by the fact that it is more difficult to protonate a double bond than an epoxide oxygen. This may also clarify why H-beta with its higher acidity gives a faster conversion of **8** and a higher selectivity to **6** than the other solid acids.

Rearrangement of Other α,β-Epoxy Ketones

Rearrangement of piperitone oxide (**9**) in the presence of various solid acids afforded two stereoisomeric forms of 3-isopropyl-1-methyl-2-oxocyclopentane-1-carbaldehyde (**10**) as major products (see Scheme 7). Like piperitone oxide itself, the two rearrangement products were very noticeable by their very pleasant odour.



9 **10**

Scheme 7. Rearrangement of piperitone oxide (**9**) to 3-isopropyl-1-methyl-2-oxocyclopentane-1-carbaldehyde (**10**)

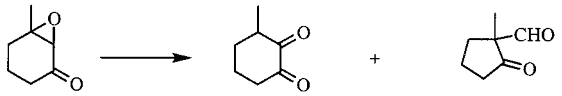
Table 3. Solid-acid catalysed rearrangement of piperitone oxide (**9**)

Catalyst	Time (min)	Conv.[a] (%)	Selectivity **10** (%)	Ratio isomers[b]
HM	120	6	80	1.4
HM[c]	30	97	78	1.6
H-beta	15	93	70	1.3
H-beta	120	100	78	1.2
Montmorillonite K10	120	14	45	1.0

[a] Performed in refluxing benzene. – [b] Determined by gas chromatography. – [c] Performed in chlorobenzene at 132 °C.

Table 3 shows that the two isomers of **10** were rapidly obtained in refluxing benzene in good selectivities when H-beta was used as a catalyst. Interestingly, no detectable amounts of deformylation products were observed. However, the use of H-mordenite and montmorillonite K10 in refluxing benzene was accompanied by low conversions. A rapid conversion of **9** over H-mordenite was observed only when the reaction was performed at a higher temperature, in refluxing chlorobenzene. Obviously, piperitone oxide is more difficult to rearrange than isophorone oxide; this is probably due to the relatively bulky isopropyl group at the 6-position, which has an unfavourable effect on the formation of the transition state for rearrangement.

2,3-Epoxy-3-methylcyclohexanone (**11**) bears a close resemblance to isophorone oxide. Indeed, rearrangement of the former compound afforded similar products to those found for isophorone oxide (see Scheme 8). Table 4 shows, however, that lower selectivities and, more strikingly, a much lower reaction rate were obtained with **11** than with isophorone oxide, upon treatment with H-mordenite in refluxing benzene (conversion of **1**: 100% after 60 min). The lower reactivity of **11** is remarkable because this epoxide is expected to fit better in a porous structure than **1**, due to its somewhat smaller size. Apparently, the presence of two methyl groups at the 5-position of isophorone oxide has a beneficial effect on the achievement of an optimum conformation for rearrangement. A recent study on the stereochemical aspects of the $BF_3 \cdot Et_2O$-catalysed rearrangement of 5-substituted 2,3-epoxycyclohexanones revealed that substituents at the 5-position indeed play an important role in directing the reaction of these conformationally constrained molecules.[17]



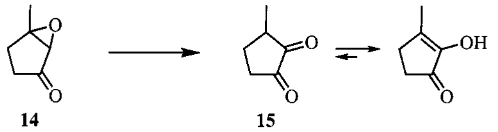
11 **12** **13**

Scheme 8. Rearrangement of 2,3-epoxy-3-methylcyclohexan-1-one (**11**) to 3-methyl-1,2-cyclohexanedione (**12**) and 1-methyl-2-oxocyclopentane-1-carbaldehyde (**13**)

Table 4. Solid-acid catalysed rearrangement of 2,3-epoxy-3-methylcyclohexan-1-one (**11**)

Catalyst	Solvent	Time (min)	Conv. (%)	Selectivity (%)	
				12	**13**
HM	benzene	30	23	6	54
HM	benzene	240	68	10	63
HM	chlorobenzene	30	99	11	75

3-Methyl-1,2-cyclopentanedione (**15**) is a flavour ingredient of maple syrup and roasted coffee,[18] and has found widespread use as a food flavour.[9] It should be noted that 1,2-dione **15** largely exists as its enolic tautomer; this propensity is often observed for 1,2-diones because, in this way, a higher degree of conjugation is obtained and dipole repulsions between the carbonyl oxygens are relieved.[19] Its synthesis has been extensively investigated and one route comprises the rearrangement of 2,3-epoxy-3-methylcyclopentanone (**14**) in the presence of acids (Scheme 9). Because of the industrial importance of this reaction, we investigated the potential of H-beta in this reaction.



14 **15**

Scheme 9. Rearrangement of 2,3-epoxy-3-methylcyclopentanone (**14**) to 3-methyl-1,2-cyclopentanedione (**15**)

Refluxing of **14** in benzene in the presence of H-beta resulted in rapid conversion of this epoxide (100% conversion after 15 min), with **15** forming as the major product. Prolongation of refluxing resulted in a gradual increase of the selectivity to **15** (84% after 180 min), again illustrating the strong adsorption behaviour of 1,2-diones on solid acids, as mentioned above.

Analogously to the rearrangement of its homologue **11** (see above), acyl migration in **14** might be expected to afford an oxocyclobutanecarbaldehyde derivative. However, such a product was not observed. Similarly, contraction of **14** to this four-ring derivative did not occur with $BF_3 \cdot Et_2O$; **15** was formed in 80% yield.[3]

Conclusions

In conclusion, we have shown that zeolite- and clay-catalysed rearrangement of cyclic α,β-epoxy ketones forms an attractive synthetic methodology. Total yields and selectivities are equal to or even better than the corresponding reactions with homogeneous reagents, but sometimes a more divergent package of products is obtained. Furthermore, the solid catalysts can be easily recovered and recycled. H-beta proved to be the most active and versatile catalyst and outer-surface passivation experiments seem to be consistent with the reaction taking place in the micropores.

Experimental Section

General: All chemicals used were analytical grade products purchased from commercial suppliers and were used without further purification. − All glassware was dried at 140 °C for at least 1 h prior to use in the catalytic reactions. − Gas chromatography (GC) analyses were performed on Varian 3400 and 3600 gas chromatographs with flame-ionisation detectors and Chrompack CP Sil 5 CB wide-bore columns (50 m × 0.53 mm) with nitrogen as carrier gas. − Gas chromatography/mass spectrometry (GC/MS) analyses were performed on a VG 70-SE mass spectrometer equipped with a CP Sil 5 CB column. The mass spectra were obtained in the electron impact (EI) mode, with 70 eV as ionisation energy. − Optical rotations were measured on a Perkin−Elmer P-141 polarimeter with ethanol as solvent. − ^1H NMR spectra of solutions in $CDCl_3$ were recorded on a Varian T-60 spectrometer (at 60 MHz), an INOVA-300 spectrometer (at 300 MHz) or a Varian VXR-400S spectrometer (at 400 MHz). − ^{13}C NMR spectra of solutions in $CDCl_3$ were recorded on an INOVA-300 spectrometer (at 75 MHz) or a Varian VXR-400S spectrometer (at 100 MHz). The chemical shifts, δ, are reported relative to tetramethylsilane (TMS). ^{13}C NMR signals were assigned with the use of the attached proton test method (APT) and correlation tables. − Column chromatography was performed with silica gel 60 (particle size 0.063−0.200 mm) from Merck. The fractions were investigated by TLC and GC. − Thin layer chromatography (TLC) was performed on precoated silica gel plates (Merck silica gel $60F_{254}$). The plates were first observed by UV (254 nm) and then by staining with a 2.5 wt-% aqueous $KMnO_4/K_2CO_3$ solution, followed by warming with a blow-drier. − The solid catalysts were characterised by X-ray powder diffraction (XRD) on a Philips PW 1877 diffractometer with Cu-K_α radiation. − The silicon, aluminium and sodium contents of the solid catalysts were determined by elemental analysis with inductive coupled plasma atomic emission spectroscopy (ICP-AES) and atomic absorption spectroscopy (AAS). The samples of the solid catalysts were prepared by successive addition of 45 mL water, 2.25 mL 20 wt-% aqueous sulfuric acid and 0.45 mL 40 wt% aqueous hydrofluoric acid to 30 mg catalyst, which was weighed into a plastic bottle. The bottle was subsequently shaken overnight at room temperature. The measurements were recorded on a Perkin−Elmer Plasma 40 (ICP-AES) or a Perkin−Elmer 1100 (AAS) instrument.

Origin of the Catalysts: Mordenite (sodium form, Si/Al = 7.3, Al/Na = 1.0) was obtained from PQ zeolites. The ammonium form of mordenite (Si/Al = 7, Al/Na = 17) was obtained by ion exchange of Na-mordenite with 1 M aqueous ammonium nitrate at 80 °C for 24 h. − Silylated mordenite was prepared from 2.5 g H-mordenite, which was stirred in a solution of 1.5 mmol tetraethyl orthosilicate in *n*-hexane (50 mL) at room temperature for 16 h. H-mordenite, for this purpose, was freshly prepared by the heating of NH_4-mordenite at 450 °C for 26 h (including heating up at 1 °C/min) and was then allowed to cool to room temperature by being exposed to the open air. After centrifugation and being washed with *n*-hexane, the zeolite was dried at 120 °C. − Dealuminated mordenite (Si/Al = 33) was prepared by the reflux of Na-mordenite in 6 M aqueous nitric acid, according to a Dow patent.[20] − Zeolite beta (Si/Al = 12, Al/Na = 10) was synthesised according to a slightly modified method of Wadlinger et al.[21] A polypropylene bottle equipped with a magnetic stirrer bar was charged with sodium aluminate (8.71 g, Riedel-de Haën, 54% Al_2O_3, 92.3 mmol Al), 40 wt-% aqueous tetraethylammonium hydroxide (82.52 g, 224 mmol) and water (5 mL). After the bottle was closed, the mixture was stirred in a boiling water bath for 1 h. The resulting clear solution was transferred to a teflon insert, which was, prior to its use, successively cleaned with diluted aqueous hydrogen fluoride (at room temperature), 2 M aqueous sodium hydroxide (at 80 °C) and copious water. Silica sol (218.72 g, Ludox LS, 30 wt%, 1092 mmol) was slowly added to this solution, which was stirred mechanically. After the immediately formed thick smooth gel was stirred at room temperature for one night, the teflon insert was placed into an autoclave and was heated at 150 °C for 166 h. A crystalline material was obtained, which was centrifuged and thoroughly washed with water until the supernatant liquid was pH-neutral. It was then dried over potassium hydroxide under vacuum. This resulted in 89 g beta in the form of a fine white powder. For complete removal of the template, the above-synthesized zeolite was subjected to three subsequent calcination steps. First, it was calcined in air to 450 °C for 23 h (heating rate 1 °C/min). After it was cooled to room temperature, a second calcination in 1% ozone in oxygen at 120 °C for 2 h took place. Finally, the zeolite was calcined in oxygen at 450 °C for 2 h (heating rate 1 °C/min). Afterwards, the zeolite was converted into its ammonium form (Si/Al = 16, Al/Na >150) by three-fold ion exchange with 1 M aqueous ammonium nitrate at 60 °C for 1 h. − NH_4-ZSM-5 (Si/Al = 45) was kindly supplied by Dr. P. J. Kunkeler, Delft University of Technology. − Zeolite NaY (Si/Al = 2.7, Al/Na = 1.0) was kindly donated by Akzo. The zeolite was exchanged with 1 M aqueous ammonium nitrate at 80 °C for 24 h resulting in $NaNH_4Y$ (Si/Al = 2.6, Al/Na = 2.9). − Montmorillonite K10 (Si/Al = 5.1, Al/Na = 45) was purchased from Fluka. The clay was washed with 1 M aqueous ammonium chloride at room temperature for 23 h to eliminate possible metal impurities (Si/Al = 4.9, Al/Na = 41).[22] − All solid catalysts were preactivated at 450 °C in a calcination oven for 17−25 h (including heating up at 1 °C/min) prior to use in the catalytic reactions. By this thermal treatment, the ammonium forms of the solids were converted into their protic forms. Silica gel was used without further activating or drying, as previously described.[11]

Isophorone Oxide (1): Isophorone oxide was synthesised by the epoxidation of isophorone with alkaline hydrogen peroxide according to a method of House and Wasson.[3,23] Because the crude isophorone oxide may contain a potentially hazardous amount of peroxide, which was not reported by House and Wasson, it was treated with aqueous sodium sulfite, to destroy peroxide impurities. During this treatment, the presence of sodium hydrogen carbonate was required to avoid the formation of bisulfite adducts. In a 2 L, three-necked flask, equipped with a dropping funnel, a stirrer, and a thermometer, was placed a solution of isophorone (111 g, 0.803 mol) and 30 wt-% aqueous hydrogen peroxide (240 mL, 2.35 mol) in 800 mL of methanol. After the contents of the flask had been cooled to 15 °C by means of an ice bath, 66 mL of 6 M aqueous sodium hydroxide was added, dropwise and with stirring, over a period of 1 h. During this addition, the temperature of the reaction mixture was maintained at 15−20 °C. After the addition was complete, the resulting mixture was stirred at the same temperature for an additional 1 h, and was then allowed to warm to room temperature and stirred overnight. The reaction mixture was then poured into 1 L of water and was extracted with diethyl ether (3×600 mL). The combined extracts were washed with water (3×800 mL), followed by addition of saturated aqueous $NaHCO_3$ (200 mL) and 20 wt% aqueous Na_2SO_3 (200 mL). The resulting mixture was vigorously stirred for one night. After separation of the water layer, the organic layer was successively washed with water (800 mL) and saturated aqueous NaCl (400 mL), and dried over anhydrous Na_2SO_4. After evaporation of the major part of the solvent, the residual liquid was distilled. The epoxide was obtained in 65% yield as a colourless oil, b.p. 75 °C/8 Torr. − ^{1}H NMR (300 MHz): $\delta = 0.92$ (s, 3 H), 1.02 (s, 3 H), 1.42 (s, 3 H), 1.70 (dd, $J = 2$ Hz, $J = 15$ Hz, 1 H), 1.81 (2d overlapping, $J = 14$ Hz, 1 H), 2.08 (d, $J = 15$ Hz, 1 H), 2.62 (d, $J = 13$ Hz, 1 H), 3.06 (s, 1 H). − ^{13}C NMR (75 MHz): $\delta = 24.1$ (CH_3), 27.9 (CH_3), 30.9 (CH_3), 36.1, 42.8 (CH_2), 48.0 (CH_2), 61.5 (CH−O), 64.3 (C−O), 207.9 (C=O). − MS; *m/z* (*%*): 154 (19) [M^+], 139 (26), 126 (15), 111 (12), 97 (29), 83 (100), 69 (54), 56 (20), 55 (37), 43 (29).

Pulegone Oxide (5, *cis/trans* = 1.7): Pulegone oxide was prepared from (*R*)-(+)-pulegone according to the procedure described above, affording a *cis/trans* mixture in a ratio of 1.7 (determined by GC). Yield 47%. The epoxide was used without further purification. The assignments *cis* and *trans* were based on measurement of the optical rotation of this mixture and known optical rotation values for the separate isomers from ref.[5] − ^{1}H NMR (300 MHz): $\delta = 1.06$ and 1.09 (d+d, $J = 6$ Hz, $J = 5$ Hz, 3 H), 1.22 (s, 1.1 H), 1.23 (s, 1.9 H), 1.44 (s, 3 H), 1.70−2.10 (m, 4 H), 2.14−2.66 (m, 3 H). − ^{13}C NMR (75 MHz): $\delta = 19.0$, 19.4, 19.7, 19.8, 20.0, 22.1, 26.4 (CH_2), 30.0 (CH_2), 30.3 (CH_2), 30.8 (CH_3), 33.1 (CH_2), 34.0 (CH_3), 49.5 (CH_2), 51.4 (CH_2), 63.2 (C−O), 63.4 (C−O), 70.1 (C−O), 70.3 (C−O), 206.4 (C=O), 207.5 (C=O). − MS; *m/z* (*%, cis*): 168 (43) [M^+], 153 (100), 125 (27), 111 (34), 98 (15), 86 (41), 83 (34), 70 (44), 69 (26), 67 (26), 55 (27), 43 (47). − MS; *m/z* (*%, trans*): 168 (41) [M^+], 153 (100), 125 (20), 111 (35), 98 (11), 86 (44), 83 (30), 70 (35), 69 (23), 67 (23), 55 (25), 43 (45).

Piperitone Oxide (9): Piperitone oxide was prepared from piperitone according to the procedure described above. Yield of crude product 41%. The product was purified by column chromatography (EtOAc/hexane = 1:5). NMR revealed the presence of two stereoisomers. − ^{1}H NMR (300 MHz): $\delta = 0.83$ (d, $J = 7$ Hz, 3 H), 0.91 (d, $J = 7$ Hz, 3 H), 1.42 (s, 0.7 H), 1.45 (s, 2.3 H), 1.50−2.50 (m, 6 H), 3.05−3.15 (m, 1 H). − ^{13}C NMR (75 MHz): $\delta = 16.9$ (CH_2), 18.2 (CH_3), 18.5 (CH_3), 20.0 (CH_3), 20.9 (CH_3), 21.8 (CH_3), 23.0 (CH_3), 23.8 (CH_2), 26.2 (CH), 27.8 (CH_2), 28.5 (CH_2), 28.9 (CH), 48.2 (CH), 52.1 (CH), 61.6 (C−O), 62.5 (CH−O, 2 ×), 65.7 (C−O), 208.5 (C=O), 209.4 (C=O).

2,3-Epoxy-3-methylcyclohexanone (11): Compound **11** was prepared from 3-methyl-2-cyclohexen-1-one according to the procedure described above. Crude yield 37%. The epoxide was used without further purification. − ^{1}H NMR (60 MHz): $\delta = 1.45$ (s, 3 H), 1.51−2.77 (m, 6 H), 3.02 (s, 1 H).

2,3-Epoxy-3-methylcyclopentanone (14): Compound **14** was prepared from 3-methyl-2-cyclopenten-1-one according to a similar procedure to that described above. The epoxide was purified by distillation. Yield 22%, b.p. 150 °C (bath temperature)/22 Torr.

Catalytic Reactions with Solid Acids: The reactions were carried out in a 250 mL three-necked, round-bottom flask equipped with a magnetic stirrer bar and a condenser fitted with a calcium chloride tube. The solid acid (0.5 g), pre-activated (450 °C, overnight), was suspended in a solution of the epoxide (10 mmol) and 1,3,5-tri-*tert*-butylbenzene (1 mmol, bulky internal standard) in benzene (50 mL). The reaction mixture was heated to the desired temperature with stirring at 1000 rpm. Aliquots were taken during the reaction and were analysed by GC. Products were isolated by column chromatography and were identified by NMR and GC/MS.

Poisoning of the catalyst was performed by stirring the catalyst in a solution of triphenylphosphane in benzene (ratio triphenylphosphane:bulk aluminium = 1−2) at room temperature for 45 min. In this case, the reaction was started by the addition of a solution of the appropriate amounts of isophorone oxide and 1,3,5-tri-*tert*-butylbenzene in benzene.

Homogeneous Rearrangement of Isophorone Oxide: The homogeneous rearrangement of isophorone oxide was based on a method of House and Wasson.[3,14] To a solution of isophorone oxide (32 mmol) in 100 mL of benzene was added $BF_3{\cdot}Et_2O$ (32 mmol). The resulting solution was mixed by swirling and was allowed to stand for 10 min. After addition of 100 mL benzene, the solution was washed with water (2×100 mL) and saturated aqueous sodium chloride solution (50 mL); it was then dried with sodium sulfate. The solution was analysed by GC using an internal standard.

Homogeneous Rearrangement of Pulegone Oxide. Synthesis of 2,2,5-Trimethylcycloheptane-1,3-dione (6): The homogeneous rearrangement of pulegone oxide was based on a method of Bach and Klix.[5] $BF_3{\cdot}Et_2O$ (32 mmol) was added to a solution of pulegone oxide (16 mmol) in 50 mL of benzene. The resulting solution was refluxed for 1 min. After addition of 50 mL benzene, the solution was washed with water (2×50 mL) and saturated aqueous sodium chloride solution (25 mL), and was then dried with sodium sulfate. Removal of the solvent, followed by chromatography over a short column afforded 2,2,5-trimethylcycloheptane-1,3-dione (**6**) as a white crystalline solid in a yield of 92% (purity 98%). − ^{1}H NMR (400 MHz): $\delta = 1.03$ (d, $J = 6.6$ Hz, 3 H), 1.23 (s+s, 6 H), 1.45−1.56 (m, 1 H), 1.94−2.10 (m, 2 H), 2.32−2.44 (m, 3 H), 2.53 (dt, $J = 2.9$ Hz, $J = 12.0$ Hz, 1 H). The ^{1}H NMR data matched with those reported.[24] − ^{13}C NMR (100 MHz): $\delta = 20.5$ (2 ×), 22.9, 35.1, 35.8, 39.8, 48.4, 61.5, 211.5, 212.5. − MS; *m/z* (*%*): 168 (35) [M^+], 153 (6), 140 (35), 125 (100), 124 (24), 123 (43), 111 (23), 97 (62), 84 (25), 83 (60), 70 (92), 69 (59), 67 (32), 55 (40), 43 (49). − $[\alpha]_D^{25\,°C} = -65.7$ ($c = 1.17$ EtOH), $[\alpha]_D^{24.5\,°C}$ (ref.[5])$= -81.8$ ($c = 1.5$ EtOH).

Identification of the Reaction Products: After the completion of the catalytic experiments, the various products were isolated from the reaction mixtures by removal of the solid catalyst (by filtration or centrifugation) and solvent (evaporation). In some cases, reactions on a larger scale were performed, without the presence of internal standard, to obtain a larger amount of a product. Where necessary, the products were subjected to further purification.

3,5,5-Trimethyl-1,2-cyclohexanedione (2): MS; *m/z* (%): 154 (91) [M^+], 139 (53), 126 (19), 125 (19), 112 (31), 111 (36), 98 (66), 83 (36), 71 (18), 70 (100), 69 (29), 55 (31), 43 (37). The MS data matched with those reported.[25]

1,4,4-Trimethyl-2-oxocyclopentane-1-carbaldehyde (3): ^{1}H NMR (60 MHz): δ = 1.03 (s, 3 H), 1.15 (s, 3 H), 1.33 (s, 3 H), 1.40−2.77 (s+m, 4 H), 9.50 (s, 1 H, CHO). The ^{1}H NMR data matched with those reported.[26] − MS; *m/z* (%): 154 (15) [M^+], 139 (5), 126 (48), 111 (19), 97 (22), 83 (100), 69 (9), 56 (15), 55 (21), 43 (21).

2,4,4-Trimethylcyclopentanone (4): Compound **4** was obtained by shaking of an ethereal solution containing **3** with 5 M aqueous sodium hydroxide (mol ratio OH^-/**3**=4) at room temperature for several minutes. The organic layer was separated, washed with saturated aqueous NaCl, dried over Na_2SO_4, and concentrated. Distillation afforded the deformylation product (**4**) as a colourless oil, b.p. 42.5 °C/8 Torr. − ^{1}H NMR (60 MHz): δ = 1.08 (s, 3 H), 1.10 (d, J = 7 Hz, 3 H), 1.17 (s, 3 H), 1.30−2.70 (s+m, 5 H). − MS; *m/z* (%): 126 (35) [M^+], 111 (11), 84 (16), 83 (96), 70 (11), 69 (73), 67 (8), 57 (21), 56 (100), 55 (61), 53 (14), 43 (10).

2-Hydroxy-2-isopropyl-5-methylcyclohexanone (8): Compound **8** was separated from 1,3-dione **6** by column chromatography (EtOAc/hexane = 1:10): R_f (**8**) < R_f (**6**). GC-analysis: t_r (**8**) > t_r (**6**). NMR revealed the presence of two stereoisomers. − ^{1}H NMR (400 MHz): δ = 0.97 (d, J = 7.1 Hz, 2.3 H, CH_3), 1.03 (d, J = 6.4 Hz, 0.7 H, CH_3), 1.40−2.76 (m, 7 H), 1.69 (s, 3 H, $CH_3{-}C{=}C$), 4.05 (br s, 0.8 H, OH), 4.14 (br s, 0.2 H, OH), 5.08−5.13 (m, 2 H, $CH_2{=}C$). The ^{1}H NMR data were in agreement with those reported.[27,28] − ^{13}C NMR (100 MHz): δ = 18.5, 18.6, 18.9, 22.2, 28.8 (CH_2), 31.6 (CH_2), 32.5 (CH_3), 33.4 (CH_2), 36.1 (CH_3), 36.9 (CH_2), 45.1 (CH_2), 46.9 (CH_2), 80.1 (C−OH), 80.4 (C−OH), 114.1 ($\mathit{C}H_2{=}C$), 114.7 ($\mathit{C}H_2{=}C$), 143.9 ($CH_2{=}\mathit{C}$), 144.1 ($CH_2{=}\mathit{C}$), 212.9 (C=O), 213.0 (C=O). − MS; *m/z* (%): 168 (20) [M^+], 153 (14), 140 (9), 125 (55), 124 (54), 123 (7), 111 (45), 97 (100), 84 (51), 83 (41), 70 (21), 69 (85), 67 (18), 55 (32), 43 (74).

3-Isopropyl-1-methyl-2-oxocyclopentane-1-carbaldehyde (10): Two isomers (A and B) of **10** were isolated with column chromatography (EtOAc/ hexane=1:5): R_f (A) > R_f (B). GC-analysis: t_r (A) < t_r (B). − **Isomer A:** ^{1}H NMR (60 MHz): δ = 0.77 (d, J = 6 Hz, 3 H), 0.95 (d, J = 6 Hz, 3 H), 1.00−3.00 (m, 6 H), 1.30 (s, 3 H), 9.35 (s, 1 H, CHO). − MS; *m/z* (%): 168 (4) [M^+], 139 (100), 97 (80), 84 (18), 71 (54), 70 (69), 69 (79), 55 (80), 43 (32). − **Isomer B:** ^{1}H NMR (60 MHz): δ = 0.70−1.18 (m, 6 H), 1.20 (s, 3 H), 1.20−3.00 (m, 6 H), 9.49 (s, 1 H, CHO). − MS; *m/z* (%): 168 (2) [M^+], 139 (100), 97 (82), 84 (17), 71 (55), 70 (71), 69 (87), 55 (93), 43 (35).

3-Methyl-1,2-cyclohexanedione (12): ^{1}H NMR (60 MHz): δ = 2.00−2.70 (m, 6 H), 1.87 (s, 3 H, CH_3), 6.16 (br s, 1 H, OH). The ^{1}H NMR data matched those reported.[29]

1-Methyl-2-oxocyclopentane-1-carbaldehyde (13): Compound **13** was separated from 1,2-dione **12** by column chromatography (EtOAc/hexane=1:5): R_f (**13**) < R_f (**12**). GC-analysis: t_r (**13**) < t_r (**12**). − ^{1}H NMR (60 MHz): δ = 1.28 (s, 3 H), 1.43−2.80 (m, 6 H), 9.42 (s, 1 H, CHO).

3-Methyl-1,2-cyclopentanedione (15): ^{1}H NMR (60 MHz): δ = 1.99 (s, 3 H), 2.39 (s, 4 H), 5.77 (br s, 1 H). The ^{1}H NMR data matched those reported.[9] − MS; *m/z* (%): 112 (100) [M^+], 97 (11), 84 (27), 83 (33), 69 (57), 56 (21), 55 (33), 43 (38).

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