

First photosensitized enantiodifferentiating isomerization by optically active sensitizer immobilized in zeolite supercages

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Enantiodifferentiating photoisomerization of (*Z*)-cyclooctene sensitized by (*R*)- or (*S*)-1-methylheptyl benzoate immobilized in zeolite supercages afforded the respective enantiomer pair, (–)- and (+)-(*E*)-isomer (**1E**) in 5% enantiomeric excess, whilst racemic **1E** was obtained upon homogeneous-phase photosensitization with the same antipodal sensitizer pair, thus demonstrating for the first time that chirally modified zeolites not only serve as supramolecular photosensitizing media but also enhance the original enantiodifferentiating ability of chiral photosensitizer.

Supramolecular asymmetric photochemistry in chirally modified zeolite media has been a field of considerable current interest.^{1,2} Ramamurthy *et al.* have recently reported the enantioselective and diastereoselective photocyclization with high enantiomeric and diastereomeric excesses.³ These asymmetric photoreactions in chirally modified zeolite media reported so far are however not ‘catalytic’ but ‘stoichiometric’, requiring at least one equivalent, or even more, chiral inductor per substrate molecule. Hence, the ‘catalytic’ enantiodifferentiating photosensitization in zeolites modified with chiral sensitizer, if achievable, becomes an attractive versatile method for transferring and multiplying molecular chirality through supramolecular interactions in the excited state.⁴

As a consequence of intensive studies on the enantiodifferentiating photosensitization in homogeneous phase, ever since the first report by Hammond and Cole in 1965,⁵ the enantiomeric excess (ee) obtained has been improved greatly in recent years.^{4,6} In particular, the enantiodifferentiating geometrical photoisomerization of (*Z*)-cyclooctene (**1Z**) sensitized by optically active (poly)alkyl benzene(poly)carboxylates gives (*E*)-isomer (**1E**) in good ee’s (Scheme 1), and the enantioselectivity is dramatically affected by environmental factors, such as temperature, pressure and solvent, accompanying a switching of product chirality in several cases.⁶

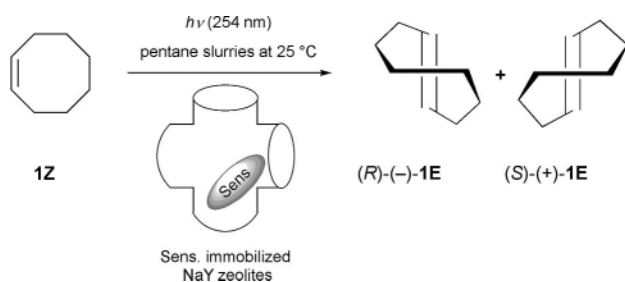
In this paper we report a novel supramolecular photochirogenesis system, in which optically active compounds, adsorbed and immobilized in zeolite supercages, sensitize the enantiodifferentiating photoisomerization of an excess amount of substrate dissolved in bulk solution. Such a ‘catalytic’ enantiodifferentiating photosensitization may be related to

enzymatic reactions, where the substrate molecule diffuses to the binding site of the enzyme and a substrate–enzyme complex is formed prior to the reaction.

The amount of sensitizer added to the zeolite was selected to achieve an average occupancy number of unity ($\langle S \rangle = 1$).⁷ The sensitizer-modified zeolites were prepared by stirring the benzene(poly)carboxylate (63 mmol) in pentane (4.0 cm³) with zeolite NaY (100 mg, activated at 450 °C) for 12 h at 25 °C. The complete adsorption and immobilization of the sensitizer into the zeolite supercages was checked and established by UV, TLC and GC analyses of the bulk solution.⁸ In the cases of methyl benzoate (**2a**), dimethyl isophthalate (**4a**) and dimethyl terephthalate (**5a**), the sensitizer was found to be efficiently immobilized into the zeolite supercages within 6 h, while only 60% immobilization of dimethyl phthalate (**3a**) was observed even after 24 h. The adsorbed benzoate and benzenedicarboxylates were completely stable in zeolite supercages and quantitatively recovered by extraction with THF even after 1 week of standing at 25 °C.

For less-bulky chiral sensitizers, such as (–)-1-methylheptyl benzoate (**2d**, **2e**), phthalate (**3d**), isophthalate (**4d**) and terephthalate (**5d**), the immobilization behavior was similar to that of the corresponding methyl esters. For bulky (–)-menthyl and (–)-bornyl benzoates (**2b** and **2c**), ca. 60–70% immobilization of sensitizer was observed, while tetramethyl benzenetetracarboxylate showed no appreciable adsorption even after 24 h at 60 °C. In sharp contrast to the strong adsorption of sensitizers, no adsorption or immobilization of (*Z*)-cyclooctene (**1Z**) was observed. The highly strained (*E*)-cyclooctene (**1E**) produced was shown to be stable in the modified zeolite supercages.

Pentane slurries (2 mL), containing **1Z** (315 mmol, or 158 mmol dm^{–3}) and NaY (100 mg) modified with sensitizer (63 mmol, $\langle S \rangle = 1$), were irradiated at 254 nm at 25 °C under an argon atmosphere to give **1E** as the sole product detected by GC. The sensitizers were stable under the irradiation conditions, as evidenced by the UV spectral and gas chromatographic examinations of THF extracts of the irradiated zeolites. The *E/Z* ratios and chemical and optical yields, obtained upon photosensitization with modified zeolite media, are listed in Table 1, along with the relevant values for the conventional sensitizations with **2d**, **4d** and **5d** in pentane solution.^{6b} The *E/Z* ratios obtained with **2a** and **4a** immobilized in the zeolite supercages are smaller than the corresponding values obtained upon photosensitization in homogeneous solutions. However, it should be noted that these low *E/Z* ratios obtained with **2a** and **4a** are not inherent to the photosensitization within the zeolite supercages, but are simply attributed to the much higher concentration employed (158 mmol dm^{–3}). Indeed, the ratio almost linearly increased with increasing irradiation time indicating that these are the initial values. It is thus concluded that the less-bulky benzenemono- and benzenedicarboxylates immobilized in the zeolite supercages work as effective sensitizers and further that the immobilized sensitizer and freely



Scheme 1

Table 1 Photosensitized isomerization of (*Z*)- and (*E*)-cyclooctene (**1Z**, **1E**) in sensitizer-immobilized zeolite cavities^a and in homogenous solutions

Media	Substrate	Sensitizer	Absolute configuration	Irradiation time/min	<i>E/Z</i>	Conversion (%)	Yield of 1E (%)	%ee ^b
Solution	1Z	2d ^c	<i>R</i>	30	0.21	22.2	16.8	-0.7
		4d ^c	<i>R</i>	60	0.32	37.9	20.0	-0.7
		5d ^c	<i>R</i>	60	0.26	46.0	14.0	-2.5
Zeolite	1Z	2a	Achiral	120	0.051	9.3	4.7	^d
		2d	<i>R</i>	120	0.021	^e	^e	-4.5
				360	0.056	^e	^e	-3.8
	1E	2d	<i>R</i>	120	2.290	^e	^e	0.0
				360	0.710	^e	^e	0.0
	1Z	2e	<i>S</i>	240	0.041	^e	^e	4.1
				360	0.054	^e	^e	4.5
		4a	Achiral	60	0.022	6.4	2.1	^d
				240	0.082	14.2	7.4	^d
				360	0.057	^e	^e	-2.5
				360	0.049	^e	^e	-3.5

^a All irradiations were conducted in pentane slurries at 25 °C. Occupancy number of sensitizer per supercage was unity. ^b Enantiomeric excess of isolated **1E** determined by chiral GC (Supelco β-Dex 225 column); error in %ee < ±0.5; the positive and negative ee values refer to the preferential formation of (*S*)-(+)- and (*R*)-(-)-**1E**, respectively; error in ee < 20% in three independent runs under identical conditions. ^c [sensitizer] = 1 mM, [**1Z**] = 5 mM in pentane at 25 °C (reference 6b). ^d Not applicable. ^e Not determined.

diffusing substrate can share the same supercage and interact with each other.

The **1E** produced was isolated from the irradiated solution through the silver nitrate extraction technique,^{6b} and was subjected to chiral GC analysis to yield the ee values shown in Table 1.⁹ A modest ee of **1E**, up to -4.5% [(-)-**1E**], was obtained for (*R*)-(-)-1-methylheptyl benzoate (**2d**)-immobilized NaY zeolite sensitization. It should be noted that this chiral sensitizer gives nearly racemic **1E** (-0.7% ee) upon irradiation in homogeneous solutions. The antipodal sensitizer pair (*R*)- and (*S*)-1-methylheptyl benzoates (**2d** and **2e**) gave the respective enantiomer pair, (-)- and (+)-**1E**, in -4.5 and +4.5% ee, respectively. Significantly, the product ee's obtained with **2d** and **2e** did not show any appreciable time dependence.

The reverse photoisomerization of **1E** with modified zeolite media was also performed under comparable conditions. Although the photoisomerization from **1E** to **1Z** occurred efficiently in the presence of **2d**-modified zeolites, no appreciable ee was observed in the remaining **1E**. (*R*)-(-)-1-Methylheptyl isophthalate (**4d**) and terephthalate (**5d**) immobilized in zeolite as sensitizer also afforded **1E** in -2.5 and -3.5% ee, respectively. In contrast to these appreciable ee's of **1E** produced in **4d**- or **5d**-modified zeolites, much lower, or nearly racemic, **1E** was produced upon sensitization with **4d** or **5d** in pentane solutions at 25 °C.

These results clearly demonstrate for the first time that the confined reaction space provided by the zeolite supercage is a convenient, versatile and reliable tool for enhancing enantio-differentiating ability of chiral sensitizers and also that such a supramolecular photosensitization system may be regarded as a 'photoenzyme', the functions of which, *i.e.* complexation and subsequent chemical transformation, are switched on by illuminating the system. Although the observed effects of confinement may not be particularly spectacular in the present cases due to the limited cavity size of NaY zeolite which bars the use of more effective chiral sensitizers such as phthalates, benzene-1,2,4,5-tetracarboxylates and benzenehexacarboxylates, it is important and essential to note that the product ee was steadily enhanced in every case, probably promising a better performance for more size-optimized sensitizer-substrate-cavity systems.

This unique aspect of immobilization of sensitizer in zeolite supercages might have mainly originated from the decrease in conformational freedom of the adsorbed sensitizer, the restricted direction of approaching **1Z** to the sensitizer, and the different exciplex structure in confined cavities. Thus, temperature effects on the enantiodifferentiating step of asymmetric photoisomerization in modified zeolite media are very inter-

esting and important points for future investigation. These effects should be different from those in homogeneous systems, and the entropy effects might be decreased in zeolite media. Temperature effects on ee in supramolecular asymmetric photoreactions in modified zeolite media are now in progress.

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- 7 The occupancy number, which is presented as <*S*>, is defined as the average number of guest molecules per supercage.
- 8 The immobilization of sensitizers into zeolite supercages was checked by TLC and GC analyses of the bulk pentane solution and the immobilized amount was qualitatively determined by UV absorption at 280 nm.
- 9 We had carefully checked the reproducibility of product ee in three independent runs under identical conditions to obtain an error well below 20% of the obtained %ee value in each case.