ARTICLE

OBC
www.rsc.org/obc

Role of cations and confinement in asymmetric photochemistry: enantio- and diastereo-selective photocyclization of tropolone derivatives within zeolites†

Abraham Joy, Lakshmi S. Kaanumalle and V. Ramamurthy*
Department of Chemistry, University of Miami, Coral Gables, FL 33124, USA.
E-mail: murthy1@miami.edu; Fax: 305 284 4571; Tel: 305 284 1534

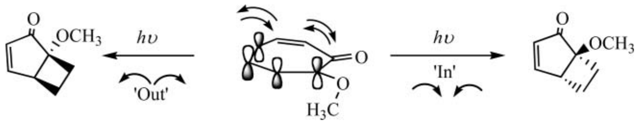
Received 7th April 2005, Accepted 14th June 2005
First published as an Advance Article on the web 13th July 2005

Asymmetric induction in photochemical reactions has been explored using the photochemistry of tropolones as a model. Three approaches have been examined: chiral inductor, chiral auxiliary and [chiral inductor + chiral auxiliary]. All three methods gave excellent asymmetric induction in zeolite and very little or zero induction in solution. Results presented on tropolones clearly illustrate the remarkable influence that a confined space studded with cations can have on asymmetric induction. Tropolone derivatives, upon irradiation undergo 4π-electron electrocyclization to yield a bicyclic product and a rearranged product. Enantiomeric excess up to 68% has been achieved in the cyclized product. In systems where a chiral inductor has been covalently linked, diastereomeric excess as high as 88% has been achieved within a zeolite while the same system in solution gave 10%.

Introduction

The past few decades have brought about an abundance of methodologies to carry out ground state reactions stereoselectively.[1,2] At the same time asymmetric photoreactions having not been investigated with the same kind of rigor have witnessed a slower advance.[3] Short lifetimes of excited states are insufficient to develop an effective interaction between the substrate and the chiral perturber. Further, the presence of small or negligible activation barriers in photochemical reactions make them more difficult to manipulate and hence imaginative methods are needed to achieve asymmetric induction in photochemical reactions. Despite all these mitigations, noteworthy progress has been made in asymmetric photoreactions in solution during the last two decades with the use of imaginative methodologies.[3] These include studies by Inoue's group wherein they have obtained 73% ee at −110 °C during geometric isomerization of *cis*-cyclooctene by chiral sensitizers.[4] Using chiral complexing agents, Bach's group has obtained remarkable success (*ca.* 90% ee at −60 °C) with several systems.[5] These include the photoaddition of 2-quinolone to alkenes (98% ee at −60 °C), cyclization of 2-pyridones (23% ee at −20 °C), and intramolecular photoaddition of 4-alkenyloxy-2-quinolones (>90% ee at −60 °C). The use of chiral auxiliaries to achieve excellent diastereoselectivity (100% de intramolecular cycloaddition) during the photocycloaddition of enones has been masterfully established by Pete and co-workers.[6] In spite of these achievements, chiral induction in photoreactions in solution is still pursued only by a few laboratories. As opposed to solution photochemistry, solid state chiral induction has been investigated for over four decades. Starting from the initial success of Schmidt and co-workers (photodimerization, e.e 70%),[7] several groups have repeatedly shown that near quantitative chiral induction could be achieved during photoreactions in crystalline state. Recent achievements of Scheffer and co-workers using ionic chiral auxiliaries[8] and by Toda and co-workers using chiral hosts have made the chiral induction studies in solid state more than a 'black art'.[9] In spite of the above studies we believe that there is still room for establishing additional methodologies for chiral induction in photochemical reactions. In this context we have explored the use of zeolites as hosts to bring about stronger interaction between a chiral perturber and the reaction site.[10] Zeolites offer a confined medium, which is in between strict solution and solid phases for conducting photoreactions of interest. In this medium, the freedom of molecules is (a) reduced compared to solution-increasing selectivity, and (b) enhanced compared to the solid state-increasing reactivity. Within zeolites even liquid samples can be 'caged' close to a chiral perturber thus making this approach more general than crystals as reaction media.

In order to establish the value of zeolites as media for achieving enantio- and diastereo-selectivity, during a photoreaction we have investigated the photocyclization of 16 α-tropolone derivatives. The photochemistry of α-tropolone ethers has been investigated in solution and organized media and the results of these experiments form the basis of the current investigation.[11–19] Upon exposure to UV light, α-tropolone ethers undergo a 4π-electron disrotatory electrocyclic ring closure to yield bicyclo[3.2.0]hepta-3,6-dien-2-ones. As a result of an equal probability of 'in' and 'out' cyclizations a racemic product mixture is obtained (Scheme 1). Although no chiral induction has been reported during solution irradiation of tropolones, significant chiral induction has been reported during the irradiation of tropolones in the solid state.[13–19] Irradiation of a solid cyclodextrin complex of tropolone methyl ether gives the cyclized product in 28% ee.[13,17] Remarkably, very high selectivity (*ca.* 90%) has been reported during the irradiation of tropolone alkyl ethers complexed to organic chiral diol hosts.[15] Using an ionic chiral auxiliary approach Scheffer and Wang have reported an ee of 60–80% during the cyclization of tropolone derivatives.[14] In this report we show that zeolites are able to bias the cyclization towards one of these two modes. The diastereomeric and enantiomeric excesses obtained in this study



Scheme 1

---

† Electronic supplementary information (ESI) available: experimental details including synthesis, characterization of reactants and characterization of photoproducts; and computational details and coordinates for the geometry optimized structures. See http://dx.doi.org/10.1039/b504865f

DOI: 10.1039/b504865f

with the tropolone derivatives within zeolites are far superior to those obtained in solution. The results discussed below provide an insight into how a zeolite is able to enforce a close interaction between a reactant and a chiral perturber.

Results

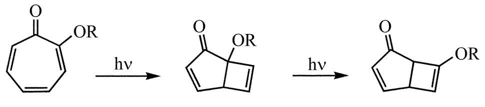
Three sets of experiments have been performed. In the first one the photochemistry of achiral tropolones within achiral zeolites in the presence of chiral inductors has been studied. In the second the photochemistry of chiral tropolones (tropolones linked with chiral auxiliaries) within achiral zeolites has been investigated. In the last set, chiral tropolones within achiral zeolites in the presence of chiral inductors have been subjected to excited state investigation. The first one is called the 'chiral inductor approach', the second the 'chiral auxiliary approach' and the last one the '[chiral auxiliary + chiral inductor] approach'. Our interest is to show the effectiveness of zeolites in inducing chiral induction during the photocyclization of tropolone derivatives.[20,21] In order to excite only the tropolone moiety, all the tropolone derivatives were irradiated using a 300 nm filter – this choice of wavelength ensured that no sensitization was involved during the reaction. The absolute configuration of the cyclized product was not known. Products were not crystalline and they could not be easily converted to crystalline derivatives. Although knowledge of the absolute configuration of the cyclized product could be very useful in determining the mechanism of chiral induction, our inability to obtain this information did not deter us from establishing the value of the zeolite-based method for achieving chiral induction in photoreactions. We wish to emphasize that the lack of information of the absolute configuration of the photo product does not decrease the value of the results presented below. In the absence of this knowledge we note the two enantiomeric or diastereomeric product peaks in GC or HPLC as A and B. The isomer that eluted first was always assigned as A.

Chiral inductor approach

Structures of the three achiral tropolone derivatives examined in the context of chiral inductor approach are provided in Scheme 2. The zeolites employed were commercially available Y samples that are not chiral. The zeolites were rendered chiral by adsorbing chiral organic molecules such as ephedrine, norephedrine and pseudoephedrine within the cages of the zeolites. Although a large number of chiral inductors were tested the best results were obtained only with the above three inductors and results from these are discussed. The experimental procedure of including the tropolone derivatives and the chiral inductor within a zeolite, irradiation procedure, extraction and analysis conditions are provided in the Experimental section. The loading level (represented as $\langle S \rangle$ and defined as the average number of molecules per supercage)[22] of the chiral inductor was maintained at one molecule in every supercage, while the loading level of the substrate was kept at one molecule in every ten supercages. A higher ratio of the chiral inductor was employed to maximize the chances of the substrate molecule being adjacent to the chiral inductor within the supercage. Sample handling was carried out under laboratory conditions ($T = 20$ °C, humidity 50%). Results of the experiments carried out with achiral tropolone derivatives are presented in Table 1. In every one of the examples, irradiation of tropolone derivatives in NaY adsorbed with the optical antipode of the chiral inductor led to the opposite enantiomer of the product with nearly the same ee [*cf.* (+) and (−) isomers of the same chiral inductor] suggesting that the systems are well behaved. With all three systems the ee obtained was dependent upon the nature of the alkali ion; for example, in the case of **1b** with ephedrine as the chiral inductor, LiY: 22%; NaY: 69%; KY: 11%; RbY: 2% (Table 2).

The effect of temperature on the reaction was examined by carrying out the irradiation at various temperatures. In the case of **1a** a decrease in temperature increased the ee whereas in **1b** it had a negligible effect. Thus the effect of temperature upon chiral induction within zeolites was not clear cut and was not pursued in detail.[23] The remarkable consequence of carrying out the reaction under anhydrous conditions is seen in Table 1. Irradiation of **1b** in NaY modified with (−)-ephedrine under dry conditions gave the product in 68% ee whereas irradiation under wet conditions gave the product in only 17% ee. A similar dramatic decrease in ee under wet conditions was also observed with **1a** and **1c**.

As a result of the absorption of light, product **2** rearranges to the isomeric chiral product **3**.[11,12] To make sure that the chiral induction in product **2** is not due to the preferential transformation of one enantiomer of **2** to **3**, irradiations of **1b** in NaY/(−)-ephedrine for varying lengths of time were carried



1a-1c **2a-2c** **3a-3c**

a. R= CH_3

b. R= CH_2CH_2Ph

c. R= CH_2COOCH_3

Scheme 2

Table 2 Cation dependence. Enantiomeric excess (%) obtained in the photoproducts **2a**–**c** during the irradiation of tropolone derivatives **1a**–**c** included in various alkali ion exchanged Y zeolites

Medium	**2a** (−)-Norephedrine	**2b** (+)-Ephedrine	**2c** (−)-Norephedrine
LiY	15 A	22 B	20 A
NaY	35 A	69 B	37 A
KY	31 A	11 B	49 A
RbY	40 A	2 B	30 A
CsY	20 A	—	7 B

Table 1 Enantiomeric excess (%) obtained in photoproducts **2a**–**c** during irradiation of tropolone derivatives **1a**–**c**[a]

Medium	Chiral inductor	**2a**[b]	**2b** (dry)	**2b** (wet)	**2c**[b]
NaY	(−)-Norephedrine at 22 °C	35 A	38 A	23 B	37 A
NaY	(+)-Norephedrine	34 B	—	—	41 B
NaY	(−)-Ephedrine	17 A	68 A	17 B	—
NaY	(+)-Ephedrine	—	69 B	—	31 B
NaY	(−)-Pseudoephedrine	1 A	20 A	8 B	28 A
NaY	(−)-Norephedrine at −40 °C	50 A	—	—	37 A
NaY	(+)-2-Amino-3-methoxy-1-phenyl-1-propanol	—	12 B	22 A	—
NaY	(+)-Diethyl tartarate	—	28 A	37 B	—

[a] (−)-Borneol and (−)-menthol gave 1–2% ee in **2a**. [b] Dry conditions.

out. When the sample was irradiated for 10 min the ee of the reaction was 78% at which time the ratio of **2b** to **3b** was 24.1 : 1. When the sample was irradiated for 45 min the ee did not change significantly (72%), but the ratio of **2b** to **3b** changed to 7 : 1. This demonstrates that the chiral induction in this reaction is a result of the interaction of the chiral inductor with the substrate and not due to preferential conversion of one enantiomer of **2** to **3**.

The following control experiments established that the enantioselectivities obtained with the achiral tropolone derivatives **1a–c** within chirally modified zeolites were not due to experimental artifacts: (a) irradiation of the tropolone derivatives in Y zeolites that had not been chirally modified yielded a racemic product mixture; (b) to ensure that one of the enantiomers did not get preferentially adsorbed within the zeolite the racemic product mixture was included within NaY modified with a chiral inductor and then extracted, and no preferential adsorption was noticed; (c) following irradiations, multiple extractions were carried out to make sure that one of the enantiomers of the product did not get preferentially adsorbed within the chirally modified zeolite.

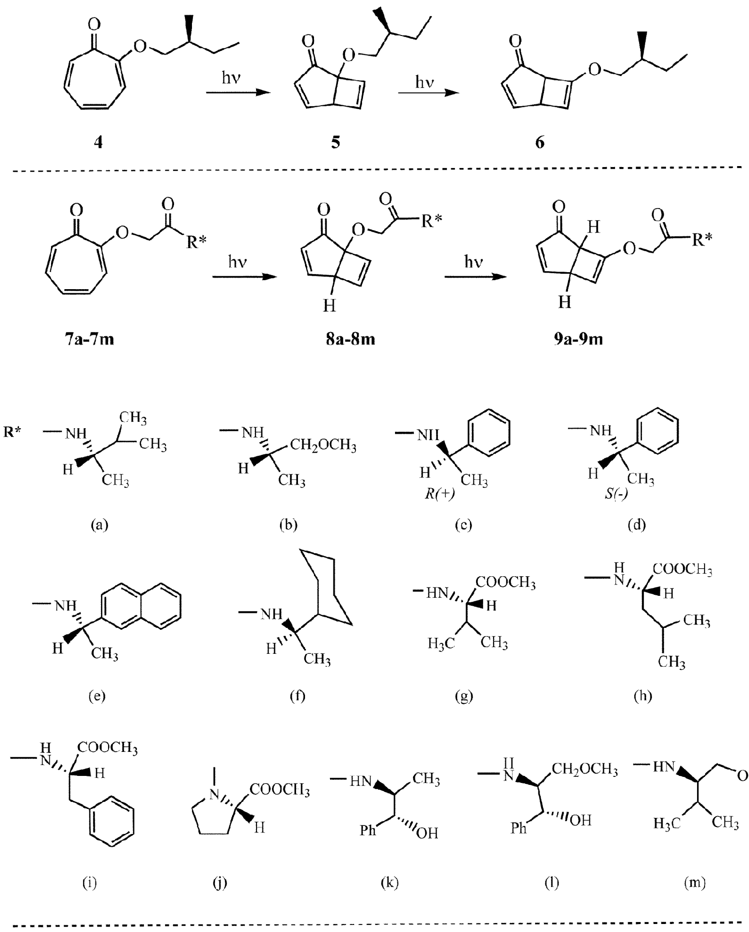
Chiral auxiliary approach

In the above experiments a chiral environment within a zeolite was created by the adsorption of a chiral organic molecule into the supercages of an achiral zeolite. Ideally the substrate and the chiral inductor should occupy the same supercage leading to the transfer of chiral information during a photochemical reaction. However, one is not certain of the location of the substrate with respect to the chiral inductor within a zeolite. Efficient chiral induction can only occur if the chiral inductor and the substrate are near one another. We present below the results of another approach that we have pursued – the chiral auxiliary approach – wherein the chiral inductor is covalently attached to the substrate. Here there is no ambiguity about the location of the substrate and the chiral source. To examine the viability of this approach the photochemical behavior of 13 tropolone derivatives (Scheme 3) covalently linked with a chiral auxiliary adsorbed within achiral LiY, NaY, KY, RbY and CsY zeolites was examined. The details of the experiments are outlined in the Experimental section and the diastereomeric excess (de) values estimated by HPLC or GC are summarized in Tables 3 and 4. As representatives of all 13 tropolone derivatives, results obtained with **4** and **7e** are highlighted below. When a chiral auxiliary is present in an optically pure form two diastereomeric products are expected. When the optical antipode of the chiral auxiliary is introduced the enantiomers of the earlier two products should be formed. Therefore, four signals are theoretically expected and in fact were observed in the case of **7c** and **7d**. We are confident that all four isomers are separated under our analysis conditions.

In spite of the tropolone ether **4** having a chiral auxiliary, irradiation in methylene choride–hexane solution led to a 1 : 1

Table 3 Amines as chiral auxiliaries. Diastereomeric excess (%) obtained in the photoproducts **8a–f** during the irradiation of tropolone derivatives **7a–f** included in various alkali ion exchanged Y zeolites

Medium	**8a**	**8b**	**8c** *R*(+)	**8d** *S*(−)	**8e**	**8f**
CH_3CN	3 A	0	2 A	—	10 A	2 B
LiY	17 B	24 B	64 B	63 A	80 B	36 B
NaY	44 B	54 B	83 B	82 A	88 B	45 B
KY	15 A	12 A	26 B	31 A	41 B	28 B
RbY	10 A	7 A	5 B	—	14 B	17 B
CsY	2 A	10 A	5 A	—	2 B	2 B



Scheme 3

Table 4 Amino acid methyl esters and amino alcohols as chiral auxiliaries. Diastereomeric excess (%) obtained in the photoproducts **8g–m** during the irradiation of tropolone derivatives **7g–m** included in various alkali ion exchanged Y zeolites

Medium	**8g**	**8h**	**8i**	**8j**	**8k**	**8l**	**8m**
CH_3CN	7 A	2 A	3 B	8 B	3 A	14 A	9 B
LiY	15 B	29 B	49 B	10 A	50 A	68 A	39 B
NaY	55 B	53 B	76 B	20 A	77 A	65 A	74 B
KY	2 B	15 B	86 B	46 B	22 A	50 A	2 A
RbY	4 B	29 A	60 B	46 B	5 B	25 A	2 A
CsY	2 B	21 A	3 B	50 B	4 B	17 A	0

diastereomeric mixture of product **5**. On the other hand, irradiation of **4** ($\langle S \rangle = 0.28$) in NaY led to the formation of **5** in 53% de. When the loading level of **4** in NaY was increased, irradiation of the NaY–**4** complex led to a decrease in the selectivity. As the loading level was increased to 0.56 and 0.83, the de decreased to 41 and 28% respectively. Irradiation of **4** in NaY, KY, RbY and CsY brought out the effect of the nature of the cation on the chiral induction. Irradiation in NaY gave the product in 53% de, whereas irradiation in KY and RbY gave the product in 21 and 12% de respectively. Irradiation in NaY, KY and RbY gave the A diastereomer as the major diastereomer, but irradiation of **4** in CsY resulted in the preferential formation of the B diastereomer (17% de).

The highest diastereoselectivity was obtained with the tropolone derivative appended with *S*(−)-naphthyl ethylamide as the chiral auxiliary (**7e**: NaY, 88%; Table 3). The same molecule in solution gave only 10%. The following observations with this system suggest that alkali metal ions present in zeolites play an important role during the asymmetric induction process. (a) The de was dependent upon the nature of the alkali metal ion (*e.g.* % de in the case of **7e** in LiY, NaY, KY, RbY and CsY were 80, 88, 41, 14 and 2 respectively; Table 3). (b) The de varied with water content of NaY used (dry: 88%; wet:10%). (c) Upon irradiation of **7e** adsorbed on silica gel, a surface that does not contain cations, the de was 0%. (d) The diastereomeric excess in the case of **7e** decreased from 88 to 40% when the Si/Al ratio of NaY zeolite was changed from 2.4 to 40. The number of cations per unit cell decreases from 56 to 5 upon changing the Si/Al ratio from 2.4 to 40.[10]

Results of the following control experiments support our conclusion that the zeolite cavity is essential to achieve significant asymmetric induction during the photochemical rearrangement of tropolone derivatives appended with a chiral auxiliary. Irradiation of (*S*)-tropolone-2-methylbutyl ether **4** in methylene chloride–hexane (1 : 4) did not yield any diastereoselectivity in the product. Irradiation of **4** (4 mg) in methylene chloride–hexane (1 : 4) containing (−)-ephedrine (25 mg) yielded a 1 : 1 racemic mixture of the product. Similarly, irradiation of **4** (4 mg) in methylene chloride–hexane (1 : 4) containing (−)-norephedrine (25 mg) yielded a 1 : 1 racemic mixture of the product. Irradiation of **4** (4 mg) and (−)-ephedrine (25 mg) adsorbed on a silica surface gave both diastereomers in equal amounts. When a 1 : 1 diastereomeric product mixture of **5** was included within NaY and extracted with diethyl ether, it was seen that the ratio of the diastereomers remained unaltered ruling out a selective adsorption of one of the diastereomers of the product. In order to prevent the first photoproduct from undergoing further rearrangement, the irradiation times were kept short (15–20 min) such that less than 20% of the secondary product was formed

[Chiral auxiliary + chiral inductor] approach

Prompted by the fact that chirally modified MY zeolites (zeolite adsorbed with a chiral inductor) brought forth asymmetric induction during the photorearrangement of achiral tropolone derivatives, we were motivated to examine their influence on chiral tropolone derivatives. For this purpose a chiral inductor and (*S*)-tropolone-2-methylbutyl ether **4** were included in NaY from hexane, the guest–NaY complex was dried under vacuum and irradiated under anhydrous conditions. Irradiation of **4** ($\langle S \rangle = 0.28$) in NaY adsorbed with (−)-ephedrine for 20 min led to the formation of the product (A isomer) in 90% de. As expected, irradiation in NaY/(+)-ephedrine led to the formation of the B isomer of the product, but with a lower de (70%). This trend was repeated in the case of norephedrine. When the irradiation was carried out in NaY/(−)-norephedrine and NaY/(+)-norephedrine the product was obtained in 92% (A) and 70% (B) respectively. When the irradiation of (*S*)-tropolone-2-methylbutyl ether **4** is carried out in NaY modified with (+)-ephedrine, there are two opposing influences in operation. The zeolite directs the reaction towards the diastereomer A while the chiral inductor directs the reaction towards the diastereomer B. To monitor the influence of these two opposing reaction forces complexes with different loading levels of the chiral inductor with a fixed amount of **4** were irradiated. Irradiations were carried out in NaY complexed with (+)-ephedrine varying between 5 and 30 mg. When the amount of (+)-ephedrine was 5 mg, the de of the reaction was 38% (A). On increasing this amount the competitive selectivity for the B diastereomer is seen. At a loading of 7 mg, which corresponds to $\langle S \rangle = 4.48$, the two opposing influences cancel each other and a 1 : 1 diastereomeric mixture is obtained. From this point onwards, the effect of the external chiral inductor overrides the influence of the zeolite and leads to a de of 75% (B) when the loading level is 30 mg of (+)-ephedrine ($\langle S \rangle = 1.03$) (Fig. 1). A similar pattern of opposing influences was observed for (+)-norephedrine. The dramatic increase in chiral induction observed within the chirally modified zeolite was not general. Irradiation in presence of (−)-pseudoephedrine, *N*-benzyl-L-prolinol, L-methylbenzyl amine and L-valinol gave the product with diastereoselectivites similar to that obtained in NaY without any chiral inductor. Chirally modified NaY had no special effect during the transformations of **7c** and **7d**. We believe that the role of the chiral inductor during phototransformation of molecules containing chiral auxiliary needs further attention.

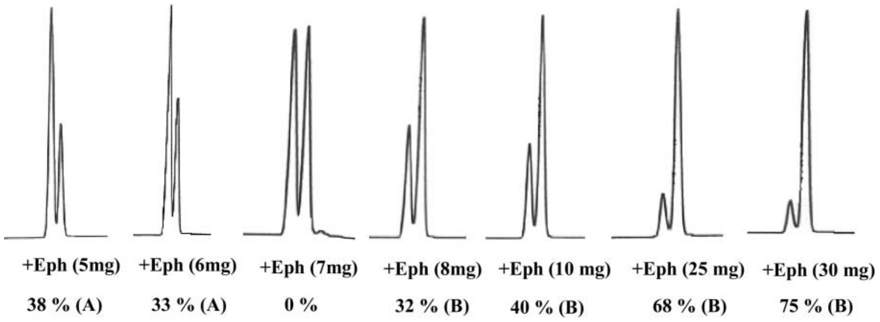


Fig. 1 GC traces (GC chiral column Supelco β-dex 325) illustrating the variation of the de as a function of the loading level of (+)-ephedrine.

Discussion

Chiral inductor approach

Results of the chiral inductor, the chiral auxiliary and the [chiral inductor + chiral auxiliary] methods as applied to tropolone derivatives are discussed independently below. This section deals with the chiral inductor approach. The results presented on three systems **1a**–**c** (Scheme 2) reveal that chiral induction during the photoreactions of achiral tropolone derivatives is significant within zeolites compared to that in solution (0% ee). The highest ee obtained was with tropolone ethyl phenyl ether **1b**. Irradiation of **1b** in NaY in the presence of (−)-ephedrine gave the product with 68% ee at 22 ° C.

We believe that the photoreaction occurs within and not on the external surface of a zeolite. Since the external surface constitutes less than 1% of the total surface area of NaY zeolite one would expect the molecules to be adsorbed on the internal rather than on the external surface. Following inclusion, washing the zeolite with hexane (in which the tropolone derivative is soluble) did not remove any molecules. If the substrate had been on the external surface it would have been dislodged easily by hexane. The effect of residual water observed in this study highlights the importance of using ‘dry’ conditions to obtain the maximum influence of a zeolite. We hypothesize that water molecules ‘turn off’ the interactions between the alkali metal ion, the tropolone derivative and the chiral inductor that are required for asymmetric induction within the zeolites (Fig. 2).

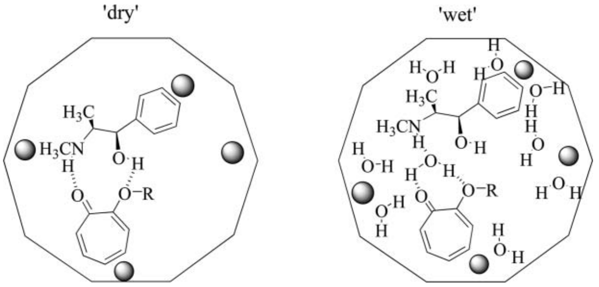


Fig. 2 Cartoon representation of tropolone methyl ether (**1a**) and ephedrine included within a supercage under wet and dry conditions. The model helps to rationalize the difference in ee obtained under the two sets of conditions. Dark circles represent the cations. Interaction between the cation, the chiral inductor and **1a** are disturbed by water molecules.

The presence of water not only influenced the extent of chiral induction, it also affected the enantiomer being enhanced. For example, in the presence of (−)-ephedrine under ‘wet’ conditions the second enantiomer (B) of the product was obtained in excess whereas under dry conditions the first enantiomer (A) of the product was obtained in excess (Table 1). This increase in enantioselectivity with a switch in the isomer being enhanced was also observed with chiral inductors such as (−)-pseudoephedrine, (−)-norephedrine, (+)-2-amino-3-methoxy-1-phenyl-1-propanol and (+)-diethyl tartrate (Table 1). Examination of Table 1 reveals that the extent of chiral induction is reactant-, chiral inductor- and alkali metal ion-specific. We have been unable to identify a universal alkali metal ion and chiral inductor that would function well for all tropolone derivatives. In spite of this deficiency the observations made are unique and novel and offers a new approach to chiral induction in photochemical reactions.

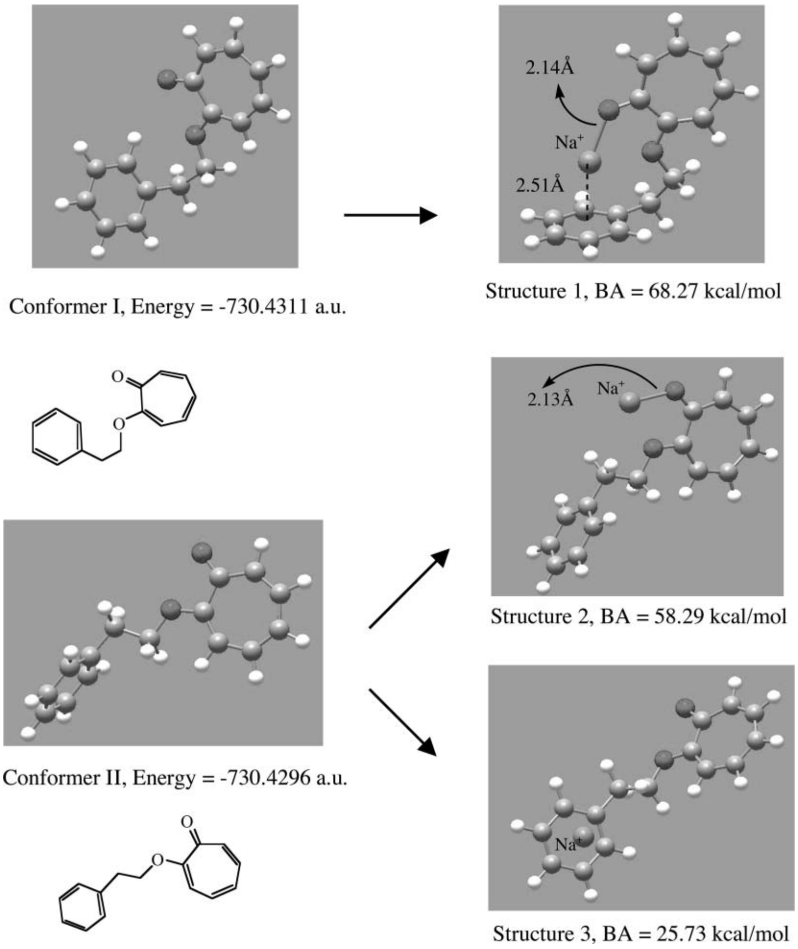
The hydrogen bonding interactions between tropolone derivatives and the chiral inductor alone are insufficient to bring about enantioselectivity. Despite the fact that such interactions are likely to be present even on a silica surface, no ee was observed in this medium with **1a**–**c**. A feature that distinguishes the zeolite surface from that of silica is the presence of alkali metal ions. Importance of alkali metal ions in the asymmetric induction process has been revealed clearly in all examples investigated in this study (Tables 1 and 2). For example, irradiation of **1c** in NaY/(−)-ephedrine gave 17% ee when the zeolite was hydrated and 68% ee when it was dry. Among the various chiral inductors examined, the ones with two functional groups such as ephedrine, pseudoephedrine, norephedrine, *etc.*, functioned better and the ones with only hydroxyl or amino groups (*e.g.* borneol, menthol, bornylamine and methylbenzyl amine) gave poor ee values (<10% in the case of **1a** and **1b**). Based on the above observation we postulate that there are multiple interactions between the achiral tropolone derivative, the chiral inductor and the alkali ion present in the zeolite interior. The recognition points are likely to be the hydroxyl, the amino and the phenyl groups of ephedrine (or norephedrine), and the phenyl ring, the ether oxygen and the carbonyl oxygen of the tropolone derivative. The chiral inductor and the tropolone derivative are held on the surface through their interaction with the alkali metal ion.

To gain an insight into the role of reactant–cation–chiral inductor interactions within zeolites we have carried out DFT calculations on the tropolone ethyl phenyl ether (**1b**)–ephedrine–NaY system using the B3LYP method and 6-31G(d) basis set (Gaussian 98 package).[24] We realize that the computational results that pertain to the gas phase are less relevant to the much more complex zeolite environment. However, in the absence of any other spectroscopic and structural data, we believe that the above gas phase computational results serve as a good starting point. Our goal was to examine whether the Na^+ ion would bring the reactant tropolone ethyl phenyl ether and the chiral inductor ephedrine close to one another. Also we were interested in obtaining a minimum energy structure of the supramolecular complex of Na^+, ephedrine and tropolone ethyl phenyl ether. One should keep in mind that within a zeolite the cations are bound to oxygens on the framework. As a result, the metal ions are likely to interact less strongly than when they are free.

Geometry optimization of tropolone ethyl phenyl ether resulted in two conformers with similar energies (Fig. 3). These conformers were allowed to interact with Na^+. Interaction of Na^+ with the conformer I resulted in one structure whereas that with the conformer II gave rise to two structures. As illustrated in Fig. 3 although the two conformers have nearly the same energies, the three structures resulting from interaction of these with Na^+ have distinctly different energies. Of these three, structure 1 in which the Na^+ interacts with the C=O and the phenyl group has the highest binding affinity. During the calculation, the metal ion was free to move to find the most stable position. Calculations did not include any structural moiety from the zeolite. At this stage our interest was to monitor computationally whether the Na^+-bound tropolone ethyl phenyl ether would interact with the chiral inductor ephedrine in any specific fashion. For this purpose (−)-ephedrine was placed closer to the Na^+-bound tropolone ethyl phenyl ether structure 1 and optimized at the RB3LYP/6-31G(d) level. This resulted in three supramolecular structures with different energies (Fig. 4). The point we wish to make is that in the most stable structure the Na^+ acts as a ‘glue’ between the chiral inductor and the reactant. In this structure there are interactions between the cation and the carbonyl and the phenyl ring of **1b**, and the amino nitrogen and the alcohol oxygen of ephedrine.[25–34] We believe that the role of the alkali metal ion is to ‘hold’ the chiral inductor near the reactant molecule in a specific geometry such that the reaction environment becomes locally chiral. The chiral induction observed within the zeolites, we hypothesize, results from such a phenomenon. In solution, the absence of such a supramolecular assembly probably leads to racemic products.

Chiral auxiliary approach

Results noted above have allowed us to recognize the need to place each reactant molecule next to a chiral inductor within a zeolite and this led us to explore the chiral auxiliary approach



Conformer I, Energy = -730.4311 a.u.

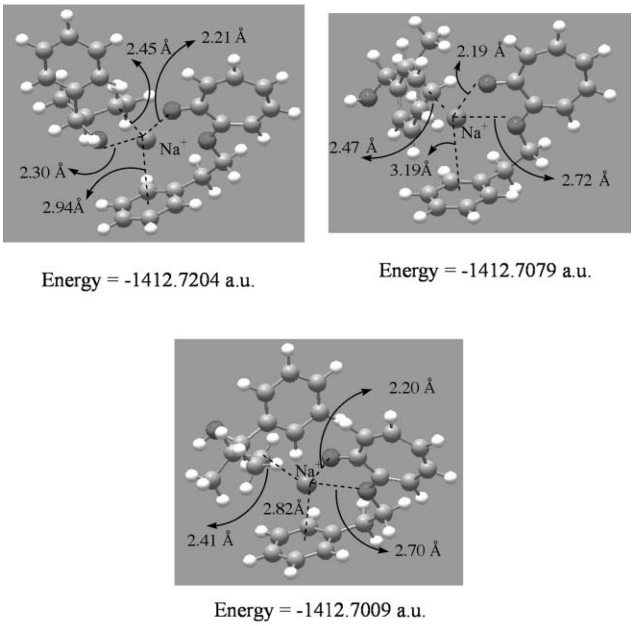
Structure 1, BA = 68.27 kcal/mol

Structure 2, BA = 58.29 kcal/mol

Conformer II, Energy = -730.4296 a.u.

Structure 3, BA = 25.73 kcal/mol

Fig. 3 Geometry optimized B3LYP/6-31G(d) structures and energies of tropolone ethyl phenyl ether (left) and geometry optimized structures and binding affinities of their Na$^+$-bound forms (right).



Energy = -1412.7204 a.u.

Energy = -1412.7079 a.u.

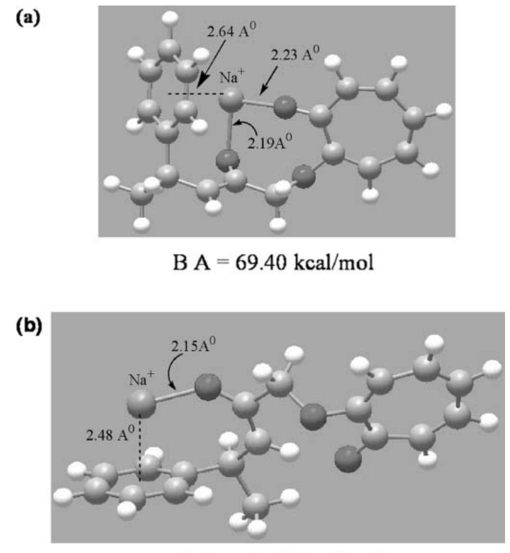
Energy = -1412.7009 a.u.

Fig. 4 Geometry optimized B3LYP/6-31G(d) structures and energies of Na$^+$-bound forms tropolone ethyl phenyl ether and (−)-ephedrine. Note that the tropolone ethyl phenyl ether and the chiral inductor (−)-ephedrine are brought closer by the alkali ion Na$^+$.

in which the chiral perturber is connected to the reactant *via* a covalent bond. In this approach, most supercages of the zeolite are expected to contain both the reactant as well as the chiral perturber. The first system we examined in this context was (*S*)-tropolone-2-methylbutyl ether (**4**). Irradiation of **4** in isotropic solvents like hexane, methylene chloride and acetonitrile gave a 1 : 1 diastereomeric mixture of the primary photoproduct (Scheme 3). Clearly the chiral center in the tropolone derivative is unable to provide chiral discrimination during the 4π-electrocyclization reaction. However, when **4** included in anhydrous MY zeolite was irradiated diastereomer A of the product was obtained in 53% excess. Simple confinement of the substrate within the reaction cavity of the zeolite has enabled the transfer of chiral information from the substituent to the reaction center. One possible mechanism for the observed diastereoselectivity in this reaction could be that one molecule in the ground state is acting as a chiral inductor for another molecule in the excited state. If this is true, one would expect the diastereoselectivity to increase with the loading level of the substrate within the zeolite. But the observation was the opposite: the diastereoselectivity for the A diastereomer decreased with the increased loading. This prompted us to conclude that the chiral center in the side chain was capable of functioning both as an external chiral inductor and as an internal chiral auxiliary and these two acts led to opposite isomers. At low loading levels a higher chiral induction could be achieved where the chiral center acts only as an internal chiral perturber (auxiliary).

It is clear that the confined medium and the cation can enforce stronger interaction between the chiral auxiliary and the reacting parts of the same molecule. To test the generality of the chiral auxiliary approach the photochemistry of 13 independent tropolone derivatives (**7a**–**m**; Scheme 3) included within achiral MY zeolites was examined. The chiral auxiliaries derived from optically pure arylamines, alkylamines, amino acid methyl esters and amino alcohols were linked to the reactive tropolone skeleton *via* an amide bond. Results presented in

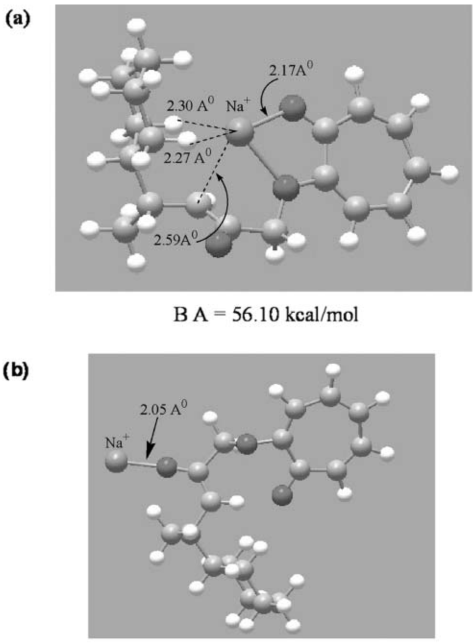
Tables 3 and 4 establish that a chiral auxiliary functions better within a zeolite than in an organic solvent. Variation in de with respect to the water content and the nature of the alkali metal ion establish that the cations present within a zeolite play an important role in the chiral induction process. Although with the results on hand we can't provide a detailed understanding of the process, we believe that we are in a position to point out some of the important factors that control the diastereoselectivity within zeolites. The chiral auxiliaries employed could be divided into two sets: one with aryl substitution and the other with alkyl substitution. Examination of Tables 3 and 4 reveals that chiral auxiliaries with aryl substitution (*e.g.* **7c**, **d**, **e**, **i**, **k** and **l**) are more effective than the ones without aryl substitution (*e.g.* **7a**, **b**, **f**, **g**, **h** and **j**) with an exception of **7m**. The ones with aryl chiral auxiliaries gave the product with a de in the range 68–88% (the best numbers are quoted) whereas the ones with alkyl chiral auxiliaries gave the product with a de in the range 46–54% (the best numbers are quoted). An insight into how cations play a role in the above chiral discrimination process is revealed by the results of *ab initio* computations of two systems, **7d** and **7f**. The binding affinities (BA values) and geometries (Figs. 5 and 6) of Na^+-bound **7d** (representing aryl chiral auxiliary) and **7f** (representing alkyl chiral auxiliary) computed at the Restricted B3LYP/6-31G(d) level provided insight into the role of the aryl group in enhancing the power of a chiral auxiliary within zeolites.[35] Both molecules interacted strongly with Na^+ with binding affinities >45 kcal mol^{-1}. Since alkali metal ions are bound to the surface of a zeolite, the binding affinities between the cation and the guest molecules within a zeolite are expected to be smaller than the values computed above, but the trend is likely to remain the same. In the most stable structure of **7d**–Na^+ the cation interacts simultaneously with the phenyl group through a cation–π interaction[25,36] as well as with the amide carbonyl and the tropolone carbonyl oxygens *via* dipolar interactions[26,33] (Fig. 5). Such interactions are expected to reduce the rotational freedom of the chiral auxiliary and thus make it 'rigid'. On the other hand, in the most stable structure of **7f**–Na^+ the cation interacts mainly with the carbonyl and ether oxygens of the tropolone (Fig. 6). Very weak interactions between the Na^+ and C–H bonds are also observable in the model. The above type of binding we believe would have very little effect on the rotational mobility of the chiral auxiliary. A model based on the alkali metal ion binding-dependent flexibility of the chiral auxiliary accounts for the observed variation in de between the aryl and alkyl chiral auxiliaries within the zeolites.



B A = 69.40 kcal/mol

B A = 62.31 kcal/mol

Fig. 5 B3LYP/6-31G(d) optimized structures of Na^+-bound **7d**.



B A = 56.10 kcal/mol

B A = 48.89 kcal/mol

Fig. 6 B3LYP/6-31G(d) optimized structures of Na^+-bound **7f**.

The alkali metal ion binding alone is unlikely to be responsible for the observed asymmetric induction for **7a**–**m** within achiral zeolites. Systems with alkyl chiral auxiliaries and **4** whose chiral auxiliary is made up of only alkyl groups gave respectable de values within zeolites (40–60%; much higher than in solution). Also, irradiation of **7e** included in NaY with only five cations per unit cell gave the product with 40% de. Although the number decreased from 88% (Si/Al ratio 2.4; number of cations per unit cell 56) to 40% it did not reach <5%, suggesting that the chiral auxiliary is more effective within zeolites than in solution even when there are no cations. Thus we conclude that the performance of a chiral auxiliary improves dramatically (with respect to solution) when its mobility is restricted through cation binding and confinement. Confinement alone improves asymmetric induction but not to the same degree as when cations are also present.

[Chiral inductor + chiral auxiliary] approach

Tropolone derivatives **4** and **7a**–**m**, in spite of having a chiral auxiliary, did not yield the product with 100% de. We believed that we could improve the asymmetric induction by including chiral tropolones within chirally modified zeolites. For this purpose we employed ephedrine and norephedrine as chiral inductors and NaY as the medium. Dramatic improvement in chiral induction was observed in the case of **4**. An insight into the process of asymmetric induction within the NaY zeolite is obtained by analyzing the results obtained in the presence and absence of ephedrine. Upon loading the zeolite with (−)-ephedrine, the inductor is expected to distribute itself within the supercages in three different ways: there could be singly occupied cages (one chiral inductor), doubly occupied cages (two chiral inductors) and empty cages (no chiral inductor). When the substrate **4** is loaded it can arrange itself among these three types of cages, and owing to space restrictions it is not expected to enter a cage that already has two chiral inductor molecules. Therefore it would be forced to enter either the single chiral inductor-occupied or empty cages. If it occupies an empty cage, upon irradiation it will give the product in *ca.* 50% de. The diastereomeric excess of 90% obtained with (−)-ephedrine could be accounted for by a distribution in which 80% of the cages are occupied by both chiral inductor and the reactant and 20% of the cages by the substrate alone. In this simple calculation we assume that cages containing the reactant and (−)-ephedrine will give the product in 100% de. This distribution is consistent with the results obtained with the optical antipode (+)-ephedrine (70% de). Had all photoreactions occurred in a single type of cage a complete switch would be expected with the antipode. This implies that we have not yet reached a condition in which every reactant site is adjacent to a chiral center.

Conclusion

In this report we have shown that the confined space offered by the zeolite supercage forces an achiral reactant and a chiral inductor to interact intimately to yield enantiomerically enriched products. Lack of chiral induction in solution suggests that such intimate interactions do not take place in this medium. Examples presented above illustrate convincingly that the influence of a chiral center present as a chiral auxiliary can be enhanced significantly when the photoreaction is carried out within a zeolite. Examination of the zeolite interior, in which the reactant molecule is held, suggests that the most likely factor responsible for the change in de. between solution and zeolite is the difference in conformational preference for the reactant molecule in these two media. In solution, the influence of cations is wiped out by solvation of the cations by the solvent molecules. Cations present in zeolites being only partially co-ordinated to the surface oxygen are free to interact with included guest molecules. Generality of the combination of chiral inductor and chiral auxiliary method that works remarkably well in the case of (*S*)-tropolone-2-methylbutyl ether is yet to be established.

Experimental

Loading and photolysis of tropolone alkyl ethers

All photolysis experiments were performed by using a 450 W medium pressure mercury lamp placed in a water-cooled Pyrex immersion well (transmits $\lambda > 290$ nm). For solution phase photolysis, the sample was taken in a Pyrex test tube and dissolved in methylene chloride–hexane (1 : 4) solution. A minimum of three samples was irradiated.

Loading and photolysis of achiral tropolone alkyl ethers (1a–c) in presence of a chiral inductors in MY zeolites

In order to activate the zeolite, commercially available NaY (300 mg) is kept in a furnace mantained at 500 °C for 12 h prior to use. The resulting activated NaY was added to the solution of the substrate, being careful not to add it too quickly which would char the sample, and not too slowly which would hydrate the zeolite from the moisture in the atmosphere. Tropolone alkyl ether (*ca.* 4 mg) and the chiral inductor (25 mg) were stirred with activated NaY (300 mg) in methylene chloride–hexane (1 : 4) for 12 h at room temperature. The loading level of the chiral inductor was maintained at one molecule in every supercage, while the loading level of the substrate was kept at one molecule in every ten supercages. A higher ratio of the chiral inductor is employed to maximize the chances of the substrate molecule being adjacent to the chiral inductor within a supercage. The zeolite containing both the reactant and the chiral inductor was collected by filtration, washed with an excess of hexane and irradiated (450 W medium pressure Hg lamp, Pyrex filter) as a hexane slurry for 2 h. Sample handling was carried out under laboratory conditions ($T = 20$ °C, humidity 55%). The product was extracted with methylene chloride and analysed by chiral GC (Supelco β-dex column). The products **2a**–**c** were characterized by comparing their ^{1}H NMR spectra to those in the literature.

Loading and irradiation of (*S*)-tropolone-2-methylbutyl ether 4 in NaY

(*S*)-Tropolone-2-methylbutyl ether (4 mg, 0.021 mmol), was dissolved in a mixture of dry methylene chloride–hexane (1 : 4). NaY (300 mg), dried at 500 °C, was added to the above. This corresponded to a loading level of $\langle S \rangle = 0.28$. The slurry was stirred for 12 h, filtered and washed with hexane (3 × 5 ml). The zeolite complexed with the tropolone ether was dried under vacuum (3×10^{-3} Torr) at 65 °C for 6 h and irradiated (450 W medium pressure Hg lamp) in dry hexane (5 ml) for 20 min. The products were extracted from the zeolite by stirring with diethyl ether.

Loading and irradiation of (*S*)-tropolone-2-methylbutyl ether 4 in the presence of a chiral inductor in NaY

(−)-Ephedrine (30 mg, 182 mmol, $\langle S \rangle = 1.0$) was dissolved in a mixture of dry methylene chloride–hexane (1 : 4). NaY (300 mg), dried at 500 °C, was added to the above. The slurry was stirred for 8 h, filtered and washed with hexane (3 × 5 ml). The zeolite modified with the chiral inductor was dried under vacuum (3×10^{-3} Torr) and added to a solution of (*S*)-tropolone-2-methylbutyl ether (4 mg, 0.021 mmol, $\langle S \rangle = 0.28$) in dry methylene chloride–hexane (1 : 4). The slurry was stirred for 12 h, filtered and washed with hexane (3 × 5 ml). The zeolite complexed with the chiral inductor and the tropolone ether was dried under vacuum (3×10^{-3} Torr) at 65 °C for 6 h and irradiated (450 W medium pressure Hg lamp) in dry hexane (5 ml) for 20 min. The products were extracted from the zeolite with diethyl ether. The chiral inductor was removed from the reaction mixture by eluting from a silical gel column (20% methlyene chloride–hexane).

Loading and irradiation of amide derivatives of 2-[(1*E*,3*Z*,5*Z*)-7-oxocyclohepta-1,3,5-trienyloxy]acetic acid (7a–m) in NaY

About 2 mg of tropolone amide derivative was taken in a test tube. To this 10 ml of methylene chloride–hexane solvent mixture (3 : 7) was added. 300 mg of activated MY zeolite was added and the contents were allowed to stir for 6–8 h. The supernatant hexane layer was tested for complete loading by removing hexane under positive pressure of nitrogen. Fresh, dry hexane (5 ml) was added and irradiated as a hexane slurry for 5 min with a 380 nm cut-off filter. The irradiation layer was removed and analysed. Products were extracted by stirring with acetonitrile.

Analysis of the photoproducts of tropolone derivatives 1a–c

The photoproducts of the irradiation were analysed by gas chromatography. A Hewlett Packard HP 5890 (FID detector) with a SE-30 column (length 30 m, id 0.32 mm, film thickness 0.25 mm) was used for product analysis. The conditions of a typical run were: initial temperature, 100 °C; intial time, 1 min; rate, 5° min^{-1}; final temperature, 250 °C; final time, 10 min.

Analysis of the enantiomeric excess of the photoproducts of tropolone derivatives 1a–c

The enantiomeric excess (ee) of a reaction is given as $(A - B/A + B) \times 100$, where A refers to the area under the first peak of the product and B refers to the area under the second peak.

1a. GC column Supelco β-dex 120 [phase, non-bonded; 20% permethylated β-cyclodextrin in SPB-35 poly(35% diphenyl/65% dimethyl siloxane)]. Initial temperature, 120 °C; initial time, 10 min; rate, 10° min^{-1}; final temperature, 130 °C; final time, 5 min; rate A: 10 °C min^{-1}; final temperature, 140 °C; final time, 15 min.

1b. HPLC chiral column OD (Chiralcel). The enantiomers of the product were resolved with hexane–*i*-PrOH (95 : 5), with a flow rate of 0.7 ml min^{-1}; detection at 254 nm.

1c. GC chiral column Supelco β dex 350. Initial temperature, 90 °C; 1 min, rate, 0.4° min^{-1}, final tempearture, 120 °C; final time, 20 min.

Analysis of the diastereomeric excess of the photoproducts of tropolone derivatives 4 and 7a–m

4. GC chiral column Supelco β-dex 325 [phase, non-bonded; 25% 2,3-di-*O*-methyl-6-*O*-TBDMS-γ-cyclodextrin in SPB-20 poly(20% phenyl/80% dimethyl siloxane)]. Initial temperature, 120 °C; initial time, 20 min; rate, 10° min^{-1}; final temperature, 130 °C; final time, 5 min; rate A: 10 °C min^{-1}; final temperature, 140 °C; final time, 30 min.

7a. HPLC column-chiralpak AD-RH; mobile phase, 95 : 5 hexane to isopropanol; flow rate = 0.5 ml min^{-1}; retention time of diastereomers, 26.5 and 29.0 min.

7b. Chiral GC column Supelco β dex 350. Temperature program: initial temperature, 100 °C; 1 min, rate 1: 5 °C min^{-1}, final temperature 1, 150 °C; final time 1, 28 min; rate 2: 20 °C min^{-1}, final temperature 2, 200 °C; final time 2, 20 min; retention time of diastereomers, 23.8 and 25.4 min.

7c. Chiral GC column Supelco β dex 350. Temperature program: initial temperature, 100 °C; 1 min, rate 1: 2 °C min^{-1}, final temperature 1, 180 °C; final time 1, 30 min; rate 2: 20 °C min^{-1}, final temperature 2, 200 °C; final time 2, 20 min; retention time of diastereomers, 42.3 and 44.6 min.

7d. Chiral GC column Supelco β dex 350. Temperature program: initial temperature, 100 °C; 1 min, rate 1: 2 °C min^{-1}, final temperature 1, 180 °C; final time 1, 30 min; rate 2: 20 °C min^{-1}, final temperature 2, 200 °C; final time 2, 20 min; retention time of diastereomers, 41.1 and 43.9 min.

7e. HPLC column-chiralpak AD-RH; mobile phase, 90 : 10 hexane to isopropanol; flow rate = 0.6 ml min^{-1}; retention time of diastereomers, 23.3 and 31.99 min.

7f. Chiral GC column Supelco β dex 350. Temperature program: initial temperature, 100 °C; 1 min, rate 1: 10 °C min^{-1}, final temperature 1, 190 °C; final time 1, 18 min; rate 2: 10 °C min^{-1}, final temperature 2, 200 °C; final time 2, 20 min; retention time of diastereomers, 22.8 and 24 min.

7g. Chiral GC column Supelco β dex 350. Temperature program: initial temperature, 100 °C; 1 min, rate 1: 5 °C min^{-1}, final temperature 1, 160 °C; final time 1, 45 min; rate 2: 10 °C min^{-1}, final temperature 2, 200 °C; final time 2, 20 min; retention time of diastereomers, 31.9 and 34.5 min.

7h. Chiral GC column Supelco β dex 350. Temperature program: initial temperature, 100 °C; 1 min, rate, 5 °C min^{-1}, final temperature, 200 °C; final time, 20 min; retention time of diastereomers, 21.3 and 21.6 min.

7i. HPLC column-chiralpak AD-RH; mobile phase, 87 : 13 hexane to isopropanol; flow rate = 0.5 ml min^{-1}; retention time of diastereomers, 24.2 and 29.8 min.

7j. HPLC column-chiralpak AD-RH; mobile phase, 85 : 15 hexane to isopropanol; flow rate = 0.5 ml min^{-1}; retention time of diastereomers, 31.3 and 34.2 min.

7k. HPLC column-chiralpak AD; mobile phase, 85 : 15 hexane to isopropanol; flow rate = 0.6 ml min^{-1}; retention time of diastereomers, 38.6 and 43.7 min.

7l. HPLC column-chiralpak AD-RH; mobile phase, 90 : 10 hexane to isopropanol; flow rate = 0.7 ml min^{-1}; retention time of diastereomers, 51.6 and 61.0 min.

7m. HPLC column-chiralpak AD; mobile phase, 85 : 15 hexane to isopropanol; flow rate = 0.5 ml min^{-1}; retention time of diastereomers, 35.8 and 40 min.

Acknowledgements

V. R. thanks the NSF for financial support (CHE-0212042).

References

1 A. Maureen Rouhi, in *Chem. Eng. News*, 2004, **82**.
2 A. Maureen Rouhi, in *Chem. Eng. News*, 2003, **81**.
3 Y. Inoue, in *Chiral Photochemistry*, Y. Inoue and V. Ramamurthy, eds., Marcell Dekker, New York, 2004, p. 129.
4 Y. Inoue, H. Ikeda, M. Kaneda, T. Sumimura, S. R. L. Everitt and T. Wada, *J. Am. Chem. Soc.*, 2000, **122**, 406.
5 B. Grosch and T. Bach, in *Chiral Photochemistry*, Y. Inoue and V. Ramamurthy, eds., Marcell Dekker, New York, 2004, pp. 315–340.
6 J.-P. Pete and N. Hoffmann, in *Chiral Photochemistry*, Y. Inoue and V. Ramamurthy, eds., Marcell Dekker, New York, 2004, pp. 179–233.
7 A. Elgavi, B. S. Green and G. M. J. Schmidt, *J. Am. Chem. Soc.*, 1973, **95**, 2058.
8 J. R. Scheffer, in *Chiral Photochemistry*, Y. Inoue and V. Ramamurthy, eds., Marcell Dekker, New York, 2004, pp. 463–483.
9 K. Tanaka and F. Toda, in *Organic Photoreactions in the Solid State*, F. Toda, ed., Kluwer, New York, 2002, pp. 109–157.
10 D. W. Breck, *Zeolite Molecular Sieves* , Robert E. Krieger, Malabar, FL, 1974.
11 O. L. Chapman and D. J. Pasto, *J. Am. Chem. Soc.*, 1960, **82**, 3642.
12 W. G. Dauben, K. Koch, S. L. Smith and O. L. Chapman, *J. Am. Chem. Soc.*, 1963, **85**, 2616.
13 H. Takeshita, M. Kumamoto and I. Kouno, *Bull. Chem. Soc. Jpn.*, 1980, **53**, 1006.
14 J. R. Scheffer and L. Wang, *J. Phys. Org. Chem.*, 2000, **13**, 531.
15 F. Toda and K. Tanaka, *Chem. Commun.*, 1986, 1429.
16 K. Tanaka, R. Nagahiro and Z. Urbanczyk-Lipkowska, *Org. Lett.*, 2001, **3**, 1567.
17 S. Koodanjeri, A. Joy and V. Ramamurthy, *Tetrahedron*, 2000, **56**, 7003.
18 F. Toda, K. Tanaka and M. Yagi, *Tetrahedron*, 1987, **43**, 1495.
19 M. Kaftory, M. Yagi, K. Tanaka and F. Toda, *J. Org. Chem.*, 1988, **53**, 4391.
20 A. Joy, J. R. Scheffer and V. Ramamurthy, *Org. Lett.*, 2000, **2**, 119.
21 A. Joy, S. Uppili, M. R. Netherton, J. R. Scheffer and V. Ramamurthy, *J. Am. Chem. Soc.*, 2000, **122**, 728.
22 J. Sivaguru, R. B. Sunoj, T. Wada, Y. Origane, Y. Inoue and V. Ramamurthy, *J. Org. Chem.*, 2004, **69**, 6533.
23 Y. Inoue, T. Yokoyama, N. Yamasaki and A. Tai, *Nature*, 1989, **341**, 225.
24 M. J. Frisch, G. W. Trucks, H. B. Schlegel, P. M. W. Gill, B. G. Johnson, M. A. Robb, J. R. Cheeseman, T. Keith, G. A. Petersson, J. A. Montgomery, K. Raghavachari, M. A. Al-Laham, V. G. Zakrzewski, J. V. Ortiz, J. B. Foresman, J. Cioslowski, B. B. Stefanov, A. Nanayakkara, M. Challacombe, C. Y. Peng, P. Y. Ayala, W. Chen, M. W. Wong, J. L. Andres, E. S. Replogle, R. Gomperts, R. L. Martin, D. J. Fox, J. S. Binkley, D. J. Defrees, J. Baker, J. P. Stewart, M. Head-Gordon, C. Gonzalez and J. A. Pople, in *Gaussian 98*, Pittsburgh, PA, 1998.
25 J. C. Ma and D. A. Dougherty, *Chem. Rev.*, 1997, **97**, 1303.
26 D. J. Raber, N. K. Raber, J. Chandrasekhar and P. V. R. Schleyer, *Inorg. Chem.*, 1984, **23**, 4076.
27 R. C. Dunbar, *J. Phys. Chem. A*, 2000, **104**, 8067.
28 F. M. Siu, N. L. Ma and C. W. Tsang, *J. Am. Chem. Soc.*, 2001, **123**, 3397.
29 R. A. Jockusch, A. S. Lemoff and E. R. Williams, *J. Am. Chem. Soc.*, 2001, **123**, 12 255.
30 T. Wyttenbach, M. Witt and M. T. Bowers, *J. Am. Chem. Soc.*, 2000, **122**, 3458.
31 R. A. Jockusch, W. D. Price and E. R. Williams, *J. Phys. Chem. A*, 1999, **103**, 9266.
32 S. Hoyau and G. Ohanessian, *Chem. Eur. J.*, 1998, **4**, 1561.
33 P. Chakrabarti and J. D. Dunitz, *Helv. Chim. Acta*, 1982, **65**, 1482.
34 E. A. Meyer, R. K. Castellano and F. Diederich, *Angew. Chem., Int. Ed.*, 2003, **42**, 1210.
35 L. S. Kaanumalle, J. Sivaguru, N. Arunkumar, S. Karthikeyan and V. Ramamurthy, *Chem. Commun.*, 2003, 116.
36 R. Chunhai and M. T. Rodgers, *J. Am. Chem. Soc.*, 2004, **126**, 14 600–14 610.