JOC Article

Enhanced Enantio- and Diastereoselectivity via Confinement and Cation Binding: Yang Photocyclization of 2-Benzoyladamantane Derivatives within Zeolites†

Arunkumar Natarajan,‡ Abraham Joy,‡ Lakshmi S. Kaanumalle,‡ John R. Scheffer,§ and V. Ramamurthy*,‡

Department of Chemistry, Tulane University, New Orleans, Louisiana 70118, and Department of Chemistry, University of British Columbia, Vancouver, BC, Canada V6T 1Z1

murthy@tulane.edu

Received June 19, 2002

Irradiation of 2-benzoyladamantane derivatives in zeolites yields the *endo*-cyclobutanols as the only photoproduct via a γ-hydrogen abstraction process. The cyclobutanols readily undergo retro-aldol reaction to give δ-ketoesters. The enantiomeric excess (ee) in the *endo*-cyclobutanols is measured by monitoring the ee in the ketoesters. Whereas in solution the ee in the product ketoester is zero, within achiral NaY zeolite, in the presence of a chiral inductor such as pseudoephedrine, ee's up to 28% have been obtained. The influence of zeolite on several chiral esters of 2-benzoyladamantane-2-carboxylic acids has also been examined. Whereas in solution the diastereomeric excess is <15%, in zeolite the δ-ketoesters are obtained in 79% de (best examples). Ab initio computations suggest that enhancement of chiral induction within zeolites is likely to be due to cation complexation with the reactant ketone. Alkali ion-organic interaction, a powerful tool, is waiting to be fully exploited in photochemical and thermal reactions. In this context zeolites could be a useful medium as one could view them as a reservoir of "naked" alkali ions that are only partially coordinated to the zeolite walls.

Introduction

During the past several years we have shown that zeolites can serve as useful media to bring about modest enantio- and diastereoselectivity during photochemical reactions.[1] A major deficiency of utilizing zeolites as reaction media for asymmetric induction is that zeolites are not chiral,[2] and this serious limitation has to be overcome. Our approach in this context has been to chirally modify the zeolite.[3] Another successful approach we have introduced is to use achiral zeolites to force an interaction between a chiral auxiliary and a reactant center in the same molecule.[4] We have shown that this "zeolite confinement strategy" is effective even when the chiral auxiliary fails to act in an isotropic solution medium.

Although they do not yet allow us to formulate basic rules regarding chiral induction within zeolites, such studies have established the potential of the zeolite-based chiral strategy.[5] Our long range objective is to develop the zeolite-based chiral strategy as a general method to conduct enantio- and diastereoselective photoreactions. This goal can be reached only when we fully understand how zeolites are able to force intimate interactions between a chiral moiety and the reaction center. In this context we have examined the photochemical behavior of 2-benzoyladamantanes **1a** and **1b** and 2-benzoyladamantane-2-carboxylic acid derivatives **5a**−**d** within faujasite zeolites (MY where M is an alkali ion).[6] Upon excitation,

* To whom correspondence should be addressed. Ph: 504 862 8135. Fax: 504 865 5596.

† Dedicated to Professor W. Adam on the occasion of his 65th birthday.

‡ Tulane University.

§ University of British Columbia.

(1) (a) Sivaguru, J.; Shailaja, J.; Uppili, S.; Ponchot, K.; Joy, A.; Arunkumar, N.; Ramamurthy, V. *Organic Solid State Reactions*; Toda, F., Ed.; Kluwer Academic Press, Norwell, MA, 2002; p 159. (b) Shailaja, J.; Sivaguru, J.; Uppili, S.; Joy, A.; Ramamurthy, V. *Mircoporous Mesoporous Mater.* **2001**, *48*, 319. (c) Joy, A.; Ramamurthy, V. *Chem. Eur. J.* **2000**, *6*, 1287.

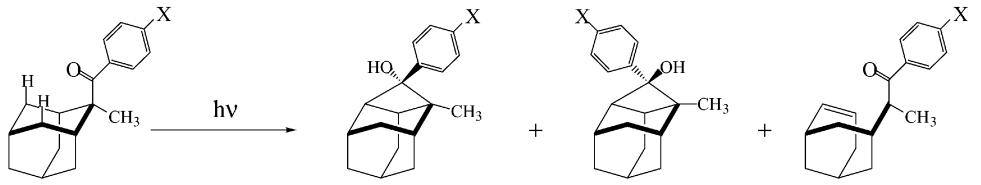
(2) Although a few chiral zeolites are known, they have not been isolated in pure chiral forms: (a) Stalder, S. M.; Wilkinson, A. P. *Chem. Mater.* **1997**, *9*, 2168. (b) Szostak, R.; *Handbook of Molecular Sieves*; Van Nostrand Reinhold: New York, 1992. (c) Tschernich, R. W. *Zeolites of the World*; Geoscience Press Inc.: Phoenix, 1992. (d) Newsam, J. M.; Treacy, M. M. J.; Koetsier, W. T.; de Gruyter, C. B. *Proc. R. Soc. London, Ser. A* **1988**, *420*, 375. (e) Anderson, M. W.; Terasaki, O.; Ohsuna, T.; Philippou, A.; MacKay, S. P.; Ferreira, A.; Rocha, J.; Lidin, S. *Nature* **1994**, *367*, 347. (f) Akporiaye, D. E. *J. Chem. Soc., Chem. Commun.* **1994**, 1711.

(3) (a) Joy, A.; Robbins, R. J.; Pitchumani, K.; Ramamurthy, V. *Tetrahedron Lett.* **1997**, 8825. (b) Joy, A.; Scheffer, J. R.; Corbin, D. R.; Ramamurthy, V. *J. Chem. Soc., Chem. Commun.* **1998**, 1379. (c) Joy, A.; Corbin, D. R.; Ramamurthy, V. In *Proceedings of 12th International Zeolite Conference*; Traecy, M. M. J., Marcus, B. K., Bisher, B. E., Higgins, J. B., Eds.; Materials Research Society: Warrendale, PA, 1999; p 2095. (d) Joy, A. Scheffer, J. R.; Ramamurthy, V. *Org. Lett.* **2000**, *2*, 119.

(4) (a) Arunkumar, N.; Wang, K.; Ramamurthy, V.; Scheffer, J. R. *Org Lett.* **2002**, *4*, 1443. (b) Sivaguru, J.; Scheffer, J. R.; Ramamurthy, V. *J. Chem. Soc., Chem. Commun.* **2002**, 830. (c) Uppili, S.; Ramamurthy, V. *Org Lett.* **2002**, *4*, 87. (d) Chong, K. C. W.; Sivaguru, J.; Shichi, T.; Yoshimi, Y.; Ramamurthy, V.; Scheffer, J. R. *J. Am. Chem. Soc.* **2002**, *124*, 2858. (e) Cheung, E.; Chong, K. C. W.; Sivaguru, J.; Ramamurthy, V.; Scheffer, J. R.; Trotter, J. *Org Lett.* **2000**, *2*, 2801. (f) Joy, A.; Uppili, S.; Netherton, M. R.; Scheffer, J. R.; Ramamurthy, V. *J. Am. Chem. Soc.* **2000**, *122*, 728.

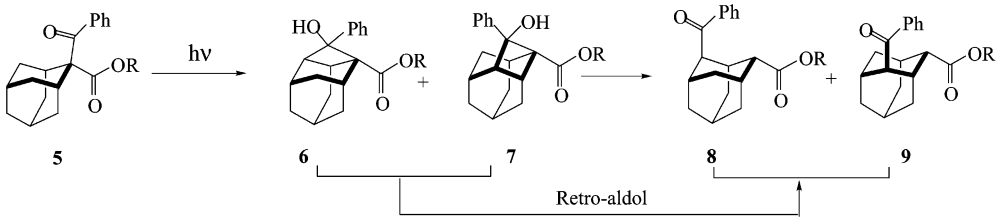
10.1021/jo0260793 CCC: $22.00
Published on Web 11/08/2002

SCHEME 1

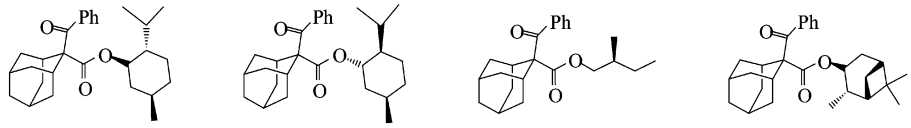


1 (a) X = H (b) X = F **2** (endo) **3** (exo) **4**

SCHEME 2

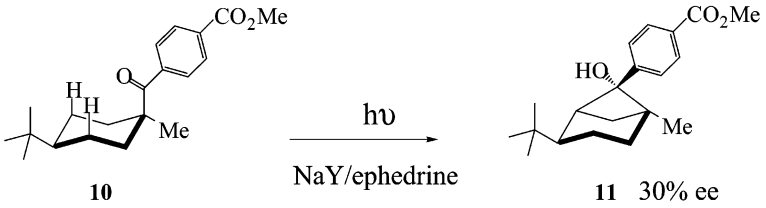


5 **6** **7** **8** **9**

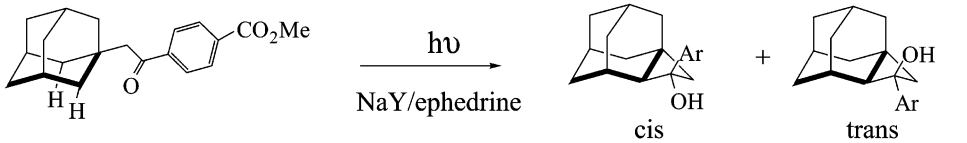


5a **5b** **5c** **5d**

SCHEME 3



10 **11** 30% ee



12 **13** 35% ee cis **14** 5% ee trans

these molecules yield cyclobutanols via γ-hydrogen abstraction (Schemes 1 and 2).[7] Cyclobutanols derived from compounds **5a**−**d** readily undergo retro-aldol reaction to yield δ-ketoesters **8** and **9** in which the chiral information is stored.[6c,8]

Previously we reported the asymmetric Yang photocyclization reactions of ketones **10** and **12** (Scheme 3).[9] Of the two, ketone **10** gives only one cyclobutanol diastereomer, both in solution and in zeolites, while ketone **12** gives two cyclobutanol diastereomers, **13** and

(5) The use of zeolites to enhance chiral induction in thermal reactions is also being explored by several groups: (a) Thomas, J. M.; Maschmeyer, T.; Johnson, B. F. G.; Shephard, D. S. *J. Mol. Catal. A. Chem.* **1999**, *141*, 139. (b) Thomas, J. M.; Raja, R. *J. Chem. Soc., Chem. Commun.* **2001**, 675. (c) Hutchings, G. J. *J. Chem. Soc., Chem. Commun.* **1999**, 301. (d) Clark, J. H.; Macquarrie, D. J. *J. Chem. Soc., Chem. Commun.* **1998**, 853. (e) Johnson, B. F. G.; Raynor, S. A.; Shephard, D. S.; Mashmeyer, T.; Thomas, J. M.; Sankar, G.; Bromley, S.; Oldroyd, R.; Gladden, L.; Mantle, M. D. *J. Chem. Soc., Chem. Commun.* **1999**, 1167. (f) Raynor, S. A.; Thomas, J. M.; Raja, R.; Johnson, B. F. G.; Bell, R. G.; Mantle, M. D. *J. Chem. Soc., Chem. Commun.* **2000**, 1925. (g) De Vos, D. E.; Meinershagen, J. L.; Bein, T. *Angew. Chem., Int. Ed. Engl.* **1996**, *35*, 2211. (h) Ogunwumi, S. B.; Bein, T. *J. Chem. Soc., Chem. Commun.* **1997**, 901. (i) Corma, A.; Iglesias, M.; del Pino, C.; Sanchez, F. *J. Chem. Soc., Chem. Commun.* **1991**, 1253. (j) Zhou, X. E.; Yu, X. Q.; Huang, J. S.; Che, C. M.; Li, S. G.; Li, L. S. *J. Chem. Soc., Chem. Commun.* **1999**, 1789. (k) Paola, P.; Langham, C.; McMorn, P.; Bethell, D.; Bulman-Page, P. C.; Hancock, F. E.; Sly, C.; Hutchings, G. J. *J. Chem. Soc., Perkin Trans. 2* **2000**, 143. (l) Paola, P.; McMorn, P.; Murphy, D.; Bethell, D.; Page, P. C. B.; Hancock, F. E.; Sly, C.; Kerton, O. J.; Hutchings, G. J. *J. Chem. Soc., Perkin Trans. 2* **2000**, 2008. (m) Kim, G. J.; Park, D. W. *Catal. Today* **2000**, *63*, 537.

(6) Photochemistry of some of these compounds in the crystalline state has been reported: (a) Leibovitch, M.; Olovsson, G.; Scheffer, J. R.; Trotter, J. *J. Am. Chem. Soc.* **1997**, *119*, 1462. (b) Leibovitch, M.; Olovsson, G.; Scheffer, J. R.; Trotter, J. *J. Am. Chem. Soc.* **1998**, *120*, 12755. (c) Cheung, E.; Netherton, M. R.; Scheffer, J. R.; Trotter, J.; Zenova, A. *Tetrahedron Lett.* **2000**, *41*, 9673.

(7) (a) Wagner, P. J.; Park, B. S. *Org. Photochem.* **1991**, *11*, 227. (b) Yang, N. C.; Yang, D. H. *J. Am. Chem. Soc.* **1958**, *80*, 2913. (c) Wagner, P. J. *Acc. Chem. Res.* **1989**, *22*, 83. (d) Scaiano, J. C. *Acc. Chem. Res.* **1982**, *15*, 252.

(8) (a) Hasegawa, T.; Arata, Y.; Endoh, M.; Yoshioka, M. *Tetrahedron* **1985**, *41*, 1667. (b) Hasegawa, T.; Nishimura, M.; Kodama, Y.; Yoshioka, M. *Bull. Chem. Soc. Jpn.* **1990**, *63*, 935.

14. The zeolites used to study these reactions were X and Y. While irradiation of compound **10** in NaY with (−)-ephedrine showed enantioselectivity in favor of the (+)-isomer of compound **11**, the same chiral inductor favored the (−)-isomer of compound **11** in NaX, although to a much smaller extent. A similar reversal was also seen when (+)-ephedrine was used as the chiral inductor. The ratio of the two cyclobutanols from ketone **12** depends on the medium in which the irradiation is conducted. In hexane, the ratio of *trans*- to *cis*-cyclobutanol is 2.8, whereas in NaY the ratio is 1.0. The results highlighted in Scheme 3 show that whereas *cis*-cyclobutanol **13** was formed in moderate enantioselectivity, the *trans* isomer **14** was formed with very low enantioselectivity. One disappointing result from these studies was that the enantiomeric excess of the cyclobutanols from ketones **10** and **12** could not be improved beyond 35%. In our continued search for a better system, we have examined the photobehavior of achiral 2-benzoyladamantanes **1a** and **1b** within chirally modified Y zeolites. To explore the versatility of the "chiral auxiliary approach" further, the photochemistry of the chiral 2-benzoyladamantane-2-carboxylic acid derivatives **5a**−**d** has been examined within achiral MY zeolites (M = alkali ion).

Results

The influence of chiral environment during the Yang photocyclization of the adamantyl ketones **1a**, **1b**, and **5a**−**d** was examined within faujasite zeolites. In the first two cases the chiral moiety that influences the reaction is an independent molecule (chiral inductor), and in the latter set of molecules it forms a part of the reactant molecule although remotely placed from the reaction center (chiral auxiliary). A typical procedure of loading the achiral ketones **1a** and **1b** within the zeolite consisted of adding activated NaY (300 mg) to a stirred hexane solution of the chiral inductor (0.1 mmol, $\langle S \rangle = 1.0$). The complexed zeolite was filtered, washed, and dried. This was added to a stirred solution of the adamantyl aryl ketone (0.01 mmol) in hexane. The loading level of the ketone was kept at one molecule for every 10 supercages ($\langle S \rangle = 0.1$). A higher ratio of the chiral inductor was employed to maximize the chances of every ketone molecule being adjacent to a chiral inductor within the supercage. The resulting doubly loaded zeolite complex was then filtered and washed with hexane. Analysis of the filtrate (hexane solution) by GC indicated that the adamantyl ketone was completely incorporated within the NaY. The zeolite complex was irradiated as a hexane slurry, the product(s) were extracted from the zeolite with diethyl ether, and the enantiomeric excess of the product determined using chiral HPLC (Chiralcel OD column). The products were identified by comparison with those obtained during crystalline irradiations and characterized previously.[6] The only products obtained upon irradiation of the above ketones in zeolites are the cyclobutanols resulting from γ-hydrogen abstraction. The dependability of the measured ee/de was checked by including a racemic or 1:1 diasteromeric mixture of the product within zeolites and reextracting them from the zeolite. The ee/de of the product included and extracted were identical, indicating that the zeolite is not selectively retaining any one isomer. By employing a calibration compound we made sure that the 95% of the included products could be re-extracted from the zeolite.

TABLE 1. Enantiomeric Excess Obtained in the Irradiation of 1a and 1b in NaY in Presence of Various Chiral Inductors[a]

chiral inductor	% ee ketone **1a**	% ee ketone **1b**
(−)-pseudoephedrine	32 (B)	30 (B)
(+)-pseudoephedrine	28 (A)	25 (A)
(+)-AMPP[b]	32 (A)	–
(+)-methyl benzyl amine	22 (A)	3 (A)
(−)-norephedrine	15 (B)	2 (A)
(+)-norephedrine	12 (A)	–
L-phenylalaninol	14 (B)	5 (B)
(+)-diethyl tartrate	11 (B)	–
L-valinol	7 (B)	–
(−)-ephedrine	2 (A)	0

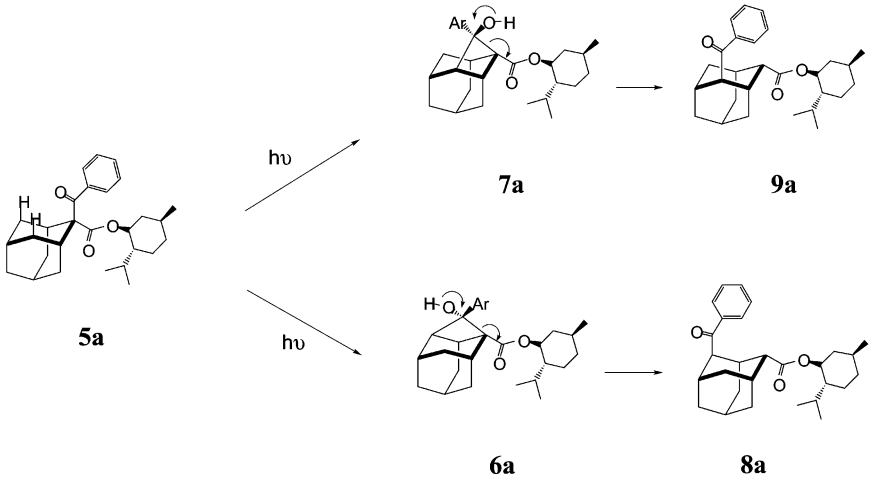
[a] The ee was determined on HPLC column OD (99% hexane−^{i}PrOH; 0.5 mL/min; 235 nm. All irradiations were carried out in NaY at 22 °C. The first peak to elute from the column is assigned as peak A and the second as B. [b] (+)-AMPP: (+)-2-amino-3-methoxy-1-phenyl-1-propanol.

The enantioselectivities induced in the cyclobutanol photoproduct from ketones **1a** and **1b** in NaY are listed in Table 1. In both cases in solution, even in the presence of chiral inductors, the cyclobutanol was formed only as a racemic mixture. However, within NaY zeolite in the presence of certain chiral inductors, an enantiomeric excess was induced in the product cyclobutanol, although only to a modest amount. Using (−)-pseudoephedrine as the chiral inductor, the product cyclobutanol from **1a** was obtained in 32% ee, while in the presence of (+)-pseudoephedrine, as expected, the opposite enantiomer was obtained in 28% ee. Irradiation with NaY/(+)-2-amino-3-methoxy-1-phenyl-1-propanol gave the product in 32% ee, while irradiation in NaY/(+)-methylbenzylamine gave the product in 22% ee. Several other chiral inductors listed in Table 1 gave poor ee's. In the case of ketone **1b** only pseudoephedrine gave the product in 30% ee; all other chiral inductors examined gave almost racemic cyclobutanol (Table 1). We are encouraged by the fact that, unlike solution, NaY is able to bring about some degree of chiral induction. At the same time we are discouraged by the observation that the extent of chiral induction is, at best, modest.

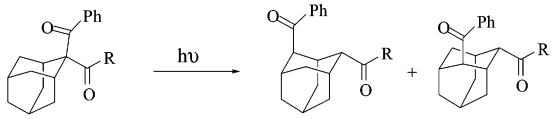
The adamantyl ketoesters derived from a (−)-menthol, (+)-isomenthol, (+)-isopinocampheol, and (−)-2-methyl-1-butanol were synthesized from adamantane-2- carboxylic acid (see Experimental Section), and their asymmetric photochemistry within MY (M = alkali ion) zeolite was investigated. A typical procedure consisted of adding activated NaY (300 mg) to a hexane solution of ketone **5** (5 mg). The solution was stirred for 12 h at 60 °C after which the zeolite complexed with ketone **5** was filtered and dried under vacuum (3×10^{-3} Torr) at 65 °C for 6 h prior to irradiation. Analysis of the filtrate (hexane) by GC indicated that only 60% of the adamantyl ketone was included within the zeolite. This could be indicative that ketone **5** is too large to fit completely within the zeolite. The same result was obtained when the loading proce-

(9) (a) Leibovitch, M.; Olovsson, G.; Sundarababu, G.; Ramamurthy, V.; Scheffer, J. R.; Trotter, J. *J. Am. Chem. Soc.* **1996**, *118*, 1219. (b) Sundarababu, G.; Leibovitch, M.; Corbin, D. R.; Scheffer, J. R.; Ramamurthy, V. *J. Chem. Soc., Chem. Commun.* **1996**, 2159.

SCHEME 4



SCHEME 5



Diastereomeric excess on the product δ-ketoesters upon irradiation of the chiral esters of 2-benzoyladamantane-2-carboxylic acids

Medium	(-) menthyl ester	(+) isomenthyl ester	S(-) 2-methylbutylester	(+) isopinocampheol ester
CH_3CN	22(A)	14(B)	5(A)	5(B)
LiY	79(B)	65(A)	26(B)	52(B)
NaY	60(B)	79(A)	54(B)	62(B)
KY	31(B)	3(A)	30(B)	4(A)

dure was repeated several times. The ketone remaining in hexane solution was removed, ketone **5** included within zeolite was irradiated (450-W medium-pressure lamp, Pyrex filter) as a hexane slurry for 60 min, and the product was extracted with THF. The conversion of the starting material to product was kept <50% in these irradiations. The isolated photoproducts in these reactions are the *δ*-ketoesters **8** and **9**, which are formed by the retro-aldol ring opening of the corresponding cyclobutanols **6** and **7** (Scheme 4). This reaction has literature precedent and the formation of *δ*-ketoesters was expected.[6c,8] The diastereoselectivity of the cyclobutanol intermediates is transformed as de in the *δ*-ketoesters, which were analyzed by HPLC.

Irradiation of 2-benzoyladamantane-2-carboxylic acid ester derivatives **5a**−**d** in acetonitrile and hexane gave the *δ*-ketoesters **8a**−**d** and **9a**−**d** in 4−22% de. Clearly, even in isotropic solution the chiral auxiliary has an influence on the asymmetric photochemistry of the parent ketone. To our delight, when these ketones were irradiated within MY zeolites (M = Li^+, Na^+, and K^+), the de obtained was substantially higher (the maximum being 79%) than in acetonitrile or hexane. The de obtained in solution and in various zeolites is summarized in Scheme 5, and typical GC or HPLC traces of the photoproducts in one zeolite and acetonitrile solution are shown in Figure 1. The figure nicely illustrates the remarkable influence of zeolites in enhancing de.

Discussion

As in isotropic solution, the 2-benzoyladamantane derivatives preferentially yield the *endo*-cyclobutanols when irradiated in zeolites.[6] Neither *exo*-cyclobutanol nor the fragmentation products are formed. Preferential formation of the *endo* product can be understood on the basis of the structural constraints on the system. This aspect of the reaction has been discussed previously in a publication by one of the current authors.[6] However, a brief discussion is appropriate.

When initially formed, the 1,4-diradical generated via *γ*-hydrogen abstraction would have its two p-orbitals perpendicular to each other in a folded conformation (Scheme 6).[7] By rotating about its central and terminal

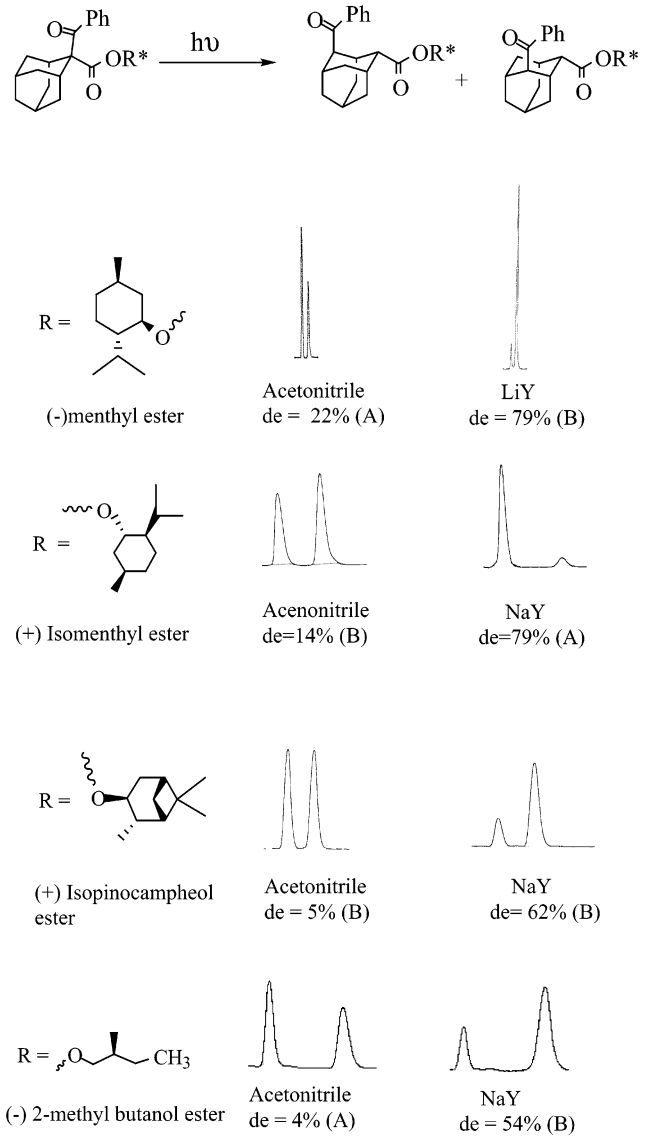
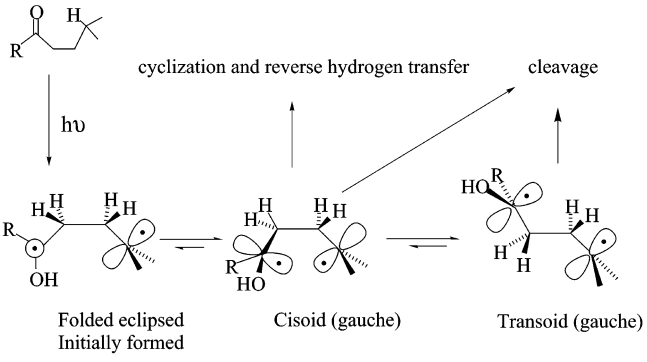


FIGURE 1. A comparison of the diastereomeric excess (de) in solution and in zeolite. GC and HPLC traces corresponding to the diastereomeric products upon irradiation of chiral esters of 2-benzoyladamatane-2-carboxylic acid. Peaks A and B correspond to the first and second diastereomers as they elute. The configurations of A and B are not known.

SCHEME 6



C—C bonds the 1,4-diradical can adopt cisoid and transoid (anti) conformations (Scheme 6). The 1,4-diradical that exists in these conformations can in principle undergo three reactions: cyclization, fragmentation, and reverse hydrogen transfer. The geometric requirements for each of these reactions are slightly different. The fragmentation process can only occur when the two p-orbitals of the 1,4-diradical are parallel to the central C—C σ-bond that is being broken. Both cyclization and reverse hydrogen transfer require that the two ends of the diradical be close to one another, i.e., it requires a cisoid conformation. Because of these constraints, the transoid conformation can only fragment, whereas the cisoid conformation can do all three, cyclization, fragmentation, and reverse hydrogen transfer (Scheme 6).

In the case of the 2-benzoyladamantyl system, because of geometric constraints the 1,4-diradical **15** generated via γ-hydrogen abstraction cannot reach the transoid geometry and also the two p-orbitals at the termini of the 1,4-diradical cannot become fully parallel to the central C—C bond (Scheme 7). However partial alignment of the orbital on C1 with the C2—C3 bond can initiate cleavage. This geometry can be reached only if the molecule can overcome an eclipsed interaction between the aryl and the R group at C2 (diradical **16** in Scheme 7). In general cleavage is not favored in systems containing methyl substitution at C2. To understand why *endo*-cyclobutanols are formed in preference to the *exo* isomers both in solution and in zeolites, one should closely examine the factors involved in the transformation of the initially formed 1,4-diradical **15** to the other conformer **17** (Scheme 7). In the minimum energy conformation computed (RB3LYP/6-31G(d)) for 2-methyl-2-benzoyl adamantane the carbonyl group is not at the center but tilted toward one of the two prochiral hydrogens (Figure 2; note the distance between the two prochiral hydrogens marked 1 and 2).[10] Excitation of the ketone present in this conformation would generate a 1,4-diradical, which cannot fragment. On the other hand, a slight tilting and rotation around the C1—C2 bond places the orbitals in an arrangement suitable for cyclization. The rotation that is needed to yield the *endo*-cyclobutanol would be expected to occur smoothly, as it involves no steric hindrance between the phenyl group and the substituent methyl group at the C2 carbon. On the other hand, the rotation that is needed to reach the diradical **17** precursor for the *exo*-cyclobutanol from the diradical **15** via the diradical **16** involves a steric interaction between the aryl group and the substituent at the C2 carbon (eclipsing interaction). Since the conformations of **15**, **16**, and **17** (initially formed, precursor for *endo* adduct, and precursor for *exo* adduct) are ideally suited for intersystem crossing from the triplet to the singlet state, the easily formed 1,4-diradical would undergo ISC and close to give

(10) Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Scuseria, G. E.; Robb, M. A.; Cheeseman, J. R.; Zakrzewski, V. G.; Montgomery, J. A., Jr.; Stratmann, R. E.; Burant, J. C.; Dapprich, S.; Millam, J. M.; Daniels, A. D.; Kudin, K. N.; Strain, M. C.; Farkas, O.; Tomasi, J.; Barone, V.; Cossi, M.; Cammi, R.; Mennucci, B.; Pomelli, C.; Adamo, C.; Clifford, S.; Ochterski, J.; Petersson, G. A.; Ayala, P. Y.; Cui, Q.; Morokuma, K.; Malick, D. K.; Rabuck, A. D.; Raghavachari, K.; Foresman, J. B.; Cioslowski, J.; Ortiz, J. V.; Stefanov, B. B.; Liu, G.; Liashenko, A.; Piskorz, P.; Komaromi, I.; Gomperts, R.; Martin, R. L.; Fox, D. J.; Keith, T.; Al-Laham, M. A.; Peng, C. Y.; Nanayakkara, A.; Gonzalez, C.; Challacombe, M.; Gill, P. M. W.; Johnson, B. G.; Chen, W.; Wong, M. W.; Andres, J. L.; Head-Gordon, M.; Replogle, E. S.; Pople, J. A. *Gaussian 98*, revision A.9; Gaussian, Inc.: Pittsburgh, PA, 1998.

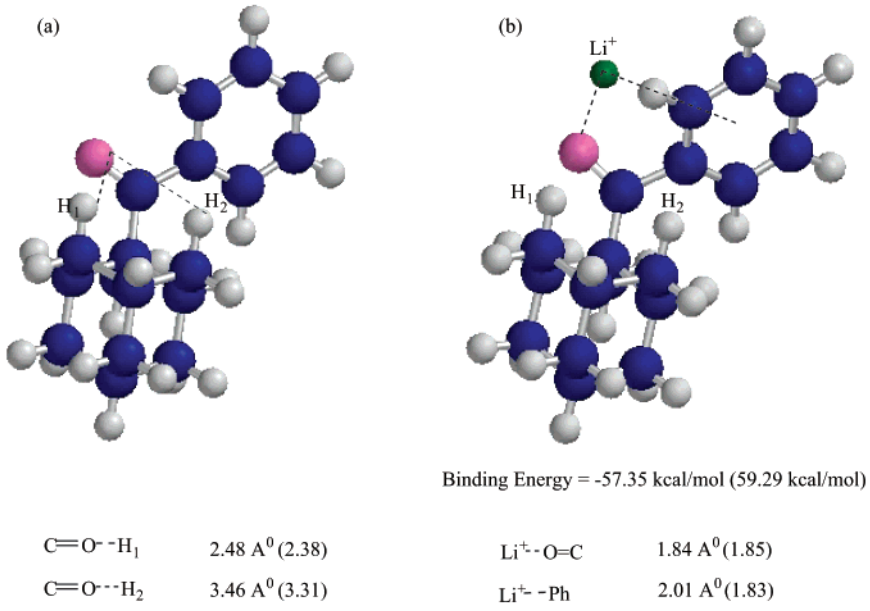
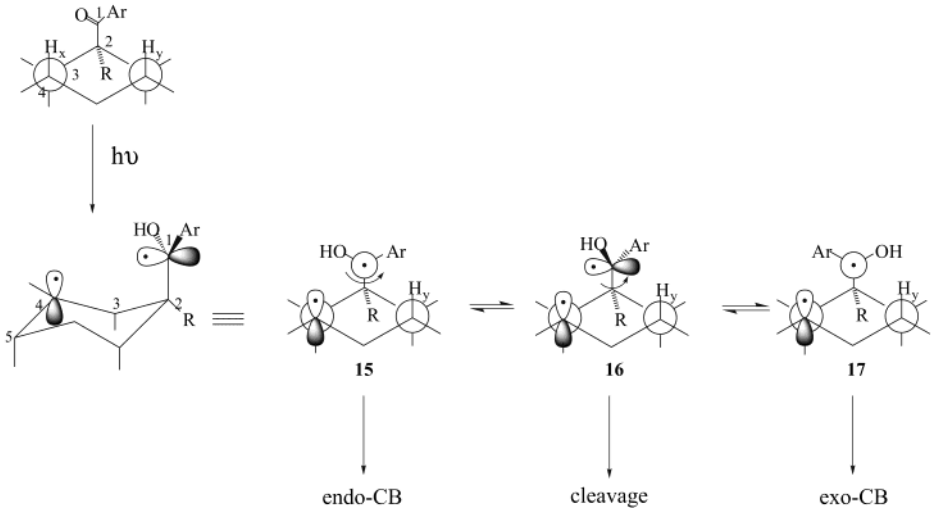


FIGURE 2. Conformation of (a) 2-methyl-2-benzoyl adamantane and its complex with Li^+ as computed at RB3LYP/6-31G(d) level. Note that the benzoyl carbonyl is tilted toward one of the two prochiral hydrogens. The distance between the carbonyl oxygen and the prochiral hydrogens are included. The binding energy computed at RHF/3-21G* level are given in paranthesis.

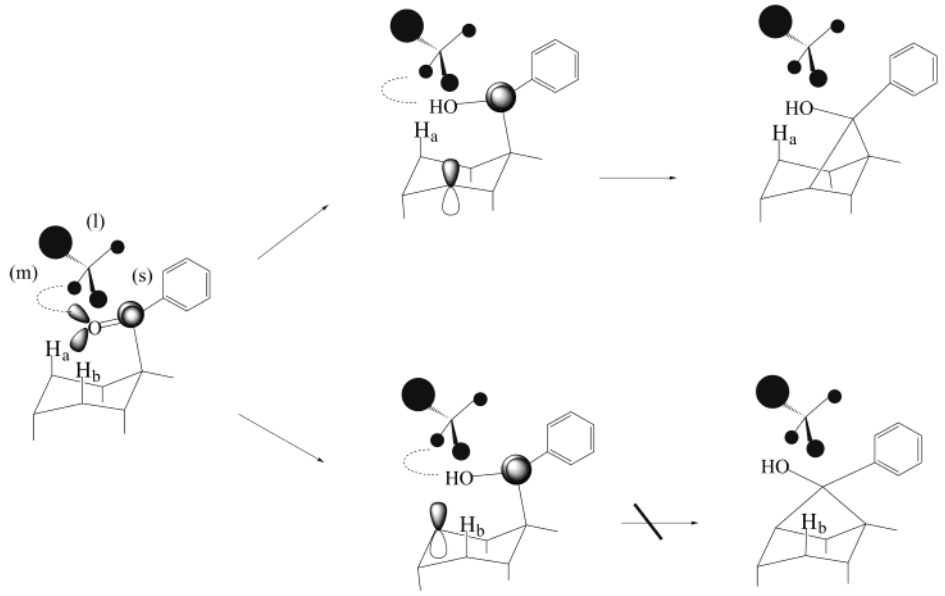
SCHEME 7



the cyclobutanol. In this case it would be the formation of the diradical **15** and the *endo*-cyclobutanol.

The final part of the discussion relates to the chiral induction during cyclobutanol formation. In the 2-benzoyladamantyl system there are two prochiral hydrogens (at C4 and C6). As mentioned above, the computed minimum energy conformation (RB3LYP/6-31G(d)) for 2-methyl-2-benzoyl adamantane indicates that the carbonyl group is tilted toward one of the two prochiral hydrogens (Figure 2). Within zeolite the cation is expected to interact with the reactant ketone **1**. The computed structure (RB3LYP/6-31G(d)) for the Li^+-2-methyl-2-benzoyl adamantane complex shown in Figure 2 also indicates that the carbonyl group is tilted toward one side. Based on symmetry the two structures in which the carbonyl group is tilted toward either C4 or C6 are of equal energy. The presence of equal amounts of the two structures would yield the *endo*-cyclobutanol as a racemic mixture, and this is what happens in the absence of a chiral influence both in solution and in zeolites. However, the presence of a chiral inductor changes the scenario. In Scheme 8, the discrimination of the diastereotopic hydrogens by the carbonyl group is illustrated in a schematic fashion. When a chiral inductor interacts weakly with the carbonyl group, the previously enantiotopic hydrogens become diastereotopic and therefore nonequivalent toward abstraction. In Scheme 8 the interacting group is marked "s" and the two diastereotopic hydrogens are marked "a" and "b". As illustrated in the Scheme, in the presence of a chiral inductor the steric environments around the two hydrogens are not the same. The C−H "a" is closer to a bulky group (marked "l"), whereas the C−H "b" is next to a less bulky group (marked "m") of the chiral inductor. This difference in environment is likely to result in preferential abstraction of one of the two hydrogens, leading to enantiomeric

SCHEME 8



excess in the product cyclobutanol.The fact that in solution, even in the presence of a chiral inductor such as pseudoephedrine, no chiral induction is obtained suggests that the interaction between the chiral inductor and the reactant is too weak to persist and that reactions occur from uncomplexed ketone molecules. We believe that the ability of zeolites to preserve this weak interaction is the basis of the observed modest chiral induction in this medium. Although we do not fully understand how zeolites are able to preserve the weak interaction between the reactant and chiral inductor molecules, we believe that the cations present in the zeolite play an important role. As seen in Table 1, the chiral inductor pseudoephedrine is able to bring about a 30% ee in the cyclobutanols derived from ketones **1a** and **1b** within NaY. This is significant, as the same chiral inductor is ineffective in acetonitrile solution.

In general, the chiral auxiliary method has given better results within zeolites than the chiral inductor approach, and the present study is no exception (Scheme 5 and Figure 1).[4] The chiral auxiliaries we have examined in this study do not contain any special chromophores. As in achiral ketone **1**, the systems with a chiral auxiliary attached to the C2 carbon should have two conformations in which the carbonyl chromophore is tilted toward one or the other diastereotopic hydrogens at C4 and C6. The two lowest energy conformations computed (RB3LYP/6-31G(d)) for the menthyl ester of 2-benzoyladamatane-2-carboxylic acid are shown in Figure 3. Clearly the carbonyl is tilted toward either side and the two conformers do not have the same energy. As indicated in Figure 3, the energy difference between the two structures is 2.3 kcal/mol. As a result of the flexible nature of the chiral auxiliary the energy difference between the two conformers must be smaller than the computed energy for the frozen conformations. This most likely results in a low de in solution.

Within zeolites the influence of the chiral auxiliary is significantly enhanced. Computational results once again provide a clue to what is likely to be responsible for the observed enhancement of de within zeolites. When the ketones are introduced within a zeolite, the cations interact with the chromophores and thus influence the conformation of the molecule. The structures of the Li^+ complex of the menthyl ester of 2-benzoyladamatane-2-carboxylic acid was computed at the RB3LYP/6-31G(d) level (Figures 4 and 5). Three structures in which the cation is bound to three different sites are identified. In structure "a" in Figure 4 the cation cooperatively interacts with the carbonyl oxygen of the ester and the phenyl group (interaction energy, −66.20 kcal/mol), and in structure "b" the interaction is primarily with the phenyl group (−47.00 kcal/mol). In structure "a" in Figure 5 the interactions are with both keto oxygen and ester oxygen (−69.90 kcal/mol). Of the structures shown in Figures 4 and 5 the ones in which the cation is interacting with both keto oxygen and ester oxygen is the most stable (Figure 5). As seen in other cases, in this structure also the keto oxygen is tilted toward one of the two prochiral hydrogens. Once again, two conformers in which the carbonyl is tilted toward either side do not have the same energy. Closer examination indicates that the nature of interaction between Li^+ and menthyl ester of 2-benzoyladamatane-2-carboxylic acid is different in the two conformers. In structure "a" the interaction is between the cation and the oxygens of the keto and ester group (CO-**O**-C), and in structure "b" the interaction is between cation and the oxygens of the two carbonyls of the keto and ester groups. The latter is more stable by 10.42 kcal/mol (compare with 2.3 kcal/mol in the absence of cation). In these structures the cation acts as "glue" to restrict the relative motions of the reactive and chiral auxiliary portions of the molecule (Figure 5). By this process the chiral auxiliary is able to exert a stronger influence on the γ-hydrogen abstraction reaction. Once interconversion between the two conformers is restricted the reaction will take place from the most stable of the two. Thus while the chiral auxiliary is essential to differentiate the two diastereotopic hydrogens, the cation is important to restrict rotations and freeze the molecule in a conformation that leads primarily to one cyclobutanol diastereomer.

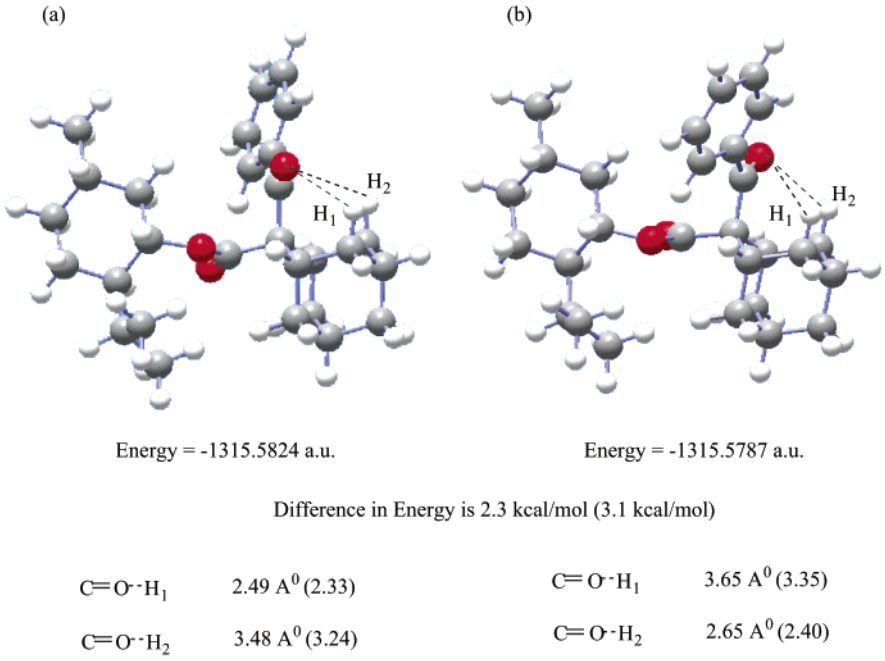


FIGURE 3. The two conformations of menthyl ester of 2-benzoyladamantane-2-carboxylic acid as computed at RB3LYP/6-31G-(d) level. Note the two conformations in which the carbonyl group is tilted toward the two prochiral hydrogens have different energies. The distance between the carbonyl oxygen and the prochiral hydrogens are included. The difference in energy computed at RHF/3-21G* level is given in parentheses.

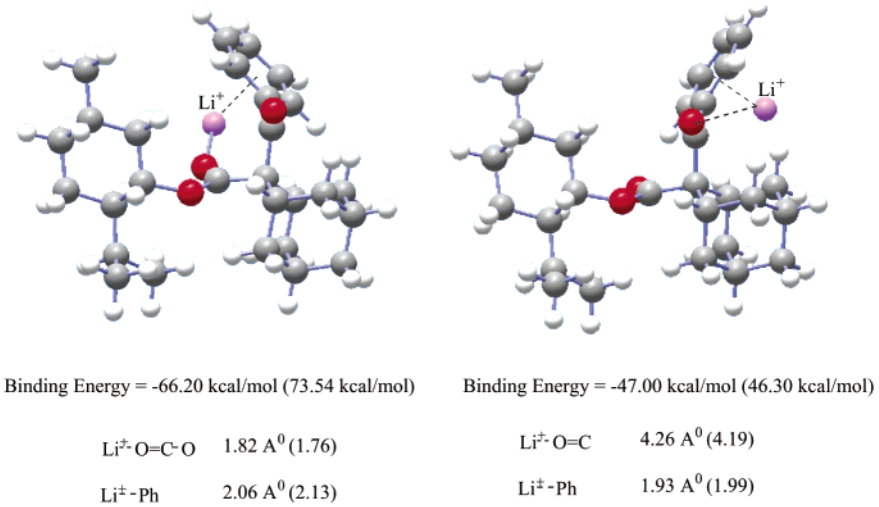


FIGURE 4. Interaction energies and structures of Li^+ complex with menthyl ester of 2-benzoyladamantane-2-carboxylic acid computed at RB3LYP/6-31G(d) level. Note that the cation location is different in the two structures and the two have different interaction energies. The interaction energies computed at RHF/3-21G* level are given in parentheses.

The dependence of the de on the cation (Scheme 5) in all four cases indicates that cation binding to the reactant molecule plays an important role in the chiral induction process within zeolites. Consistent with this conclusion is the finding that inclusion of water into NaY along with the ketone **5** decreases the de to <10%. In the presence of water the cation would preferentially bind to water molecules and thus would have no influence on the diastereoselectivity. On the basis of the admittedly limited number of examples discussed above we tentatively conclude that the size and rigidity of the chiral auxiliary is important. For example, among the compounds **5a**−**d**, the smaller and more flexible 2-methylbutyl chiral auxiliary (compound **5c**) gives the lowest de. We recognize that a comprehensive model for chiral induction within zeolites is still far from complete, and only small pieces such as those presented here help build a bigger picture.

The above results suggest that divalent cations such as Mg^{2+}, Ca^{2+}, and others would provide a much better selectivity within zeolites. Unfortunately, the use of such divalent and trivalent cation exchanged zeolites generate Brønsted acid sites upon activation.[11] The use of zeolites containing Brønsted acid sites are not useful as media

(11) Kao, H. M.; Grey, C. P.; Pitchumani, K.; Lakshminarasimhan, P. H.; Ramamurthy, V. *J. Phys. Chem.* **1998**, *102*, 5627.

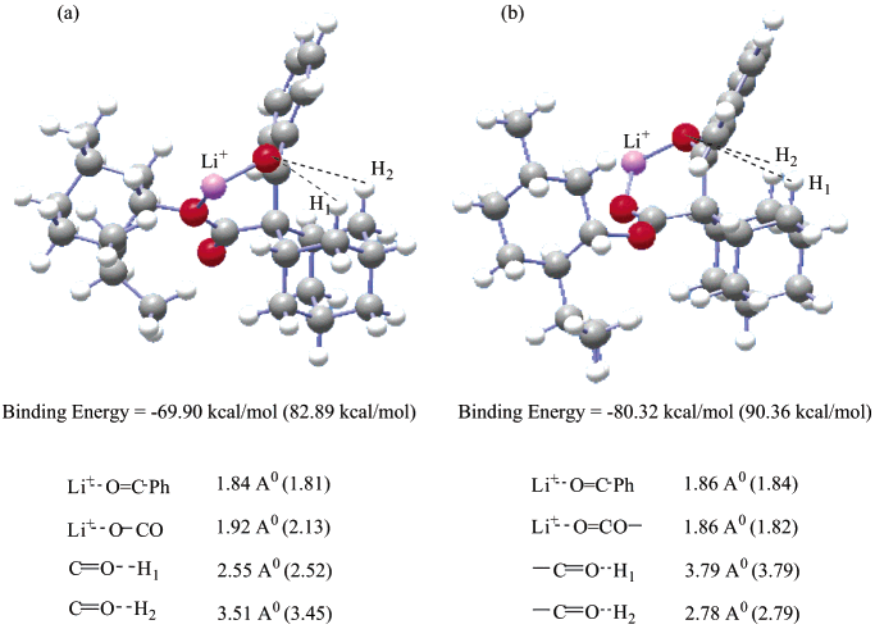


FIGURE 5. The most stable structure computed (RB3LYP/6-31G(d)) for Li^+ complex with menthyl ester of 2-benzoyladamantane-2-carboxylic acid. In the two structures the sites of interaction of Li^+ are different. The carbonyl is tilted toward different prochiral hydrogens in the two structures. Note the interaction energies are considerably different for the two structures. The interaction energies computed at RHF/3-21G* level are given in parentheses.

for photochemical reactions because thermal dark reactions predominate.[12]

Conclusion

The examples presented above demonstrate convincingly that the confined space of a zeolite can serve as a useful medium to achieve asymmetric induction during a photoreaction. Consistently higher ee's or de's have been obtained within zeolites than those in solution. Of the two approaches presented, the chiral auxiliary method gives better results. The confined space and the cations present within zeolites are believed to be responsible for the asymmetric induction. Although a model that can predict the outcome of asymmetric induction with zeolites as reaction media is currently lacking, experiments in this direction are underway.

In the past, chiral solvents, chiral auxiliaries, circularly polarized light, and chiral sensitizers have been utilized to conduct enantioselective photoreactions.[13] The highest chiral induction achieved by any of these approaches at ambient temperature and pressure is ~30% (2−10% ee is common in photochemical reactions under the above conditions). The crystalline state[14,15] and solid host−guest assemblies[16] have, on the other hand, provided the most encouraging results. Consistently high (>90%) ee's have been obtained in a number of photoreactions. Even though crystalline and host−guest assemblies have been very useful in conducting enantioselective photoreactions, their general applicability thus far has been limited. They are restricted to systems that form crystalline materials. We believe that the zeolite approach presented here can serve as a complimentary method to the solid-state approach. In principle, zeolites could serve as chiral media to reactants present in any state (gas, liquid, or solid). We are, however, still far from realizing the desired goal of quantitative ee or de in a photochemical reaction.

Experimental Section

Materials. NaY zeolite was obtained from a commercial source. Monovalent cation exchanged zeolites (LiY, KY, RbY, and CsY) were prepared by stirring 10 g of NaY with 100 mL of a 10% solution of the corresponding metal nitrate in water for 12 h with continuous refluxing. The zeolite was filtered and washed thoroughly with distilled water. This procedure was repeated three times. Subsequently, the zeolite was dried at 120 °C for about 3 h to obtain the cation exchanged zeolite.

Synthesis of Adamantyl Phenyl Ketones. (a) Synthesis of 2-Benzoyl-2-methyladamantane (1a). The procedure adopted in this study is slightly different from the one published previously.[6b] The overall scheme used to synthesize the reactants is outlined in Scheme 9. The method of Alberts et al.[17] was used to prepare the adamantane 2-carboxaldehyde. A dry three-necked 250-mL round-bottomed flask was charged with methoxymethyltriphenylphosphinechloride, CH_3OCH_2P-

(12) Ramamurthy, V.; Lakshminarasimhan, P. H.; Grey, C. P.; Johnston, L. J. *J. Chem. Soc., Chem. Commun*. **1998**, 2411.

(13) (a) Inoue, Y. *Chem. Rev*. **1992**, *92*, 741. (b) Rau, H. *Chem. Rev*. **1983**, *83*, 535. (c) Pete, J. P. *Adv. Photochem*. **1996**, *21*, 135. (d) Everitt, S. R. L.; Inoue, Y. In *Molecular and Supramolecular Photochemistry*; Ramamurthy, V., Schanze, K. S., Eds.; Marcell Dekker: New York, 1999; Vol. 3, p 71. (e) Buschmann, H.; Scharf, H. D.; Hoffmann, N.; Esser, P. *Angew. Chem., Int. Ed. Engl*. **1991**, *30*, 477.

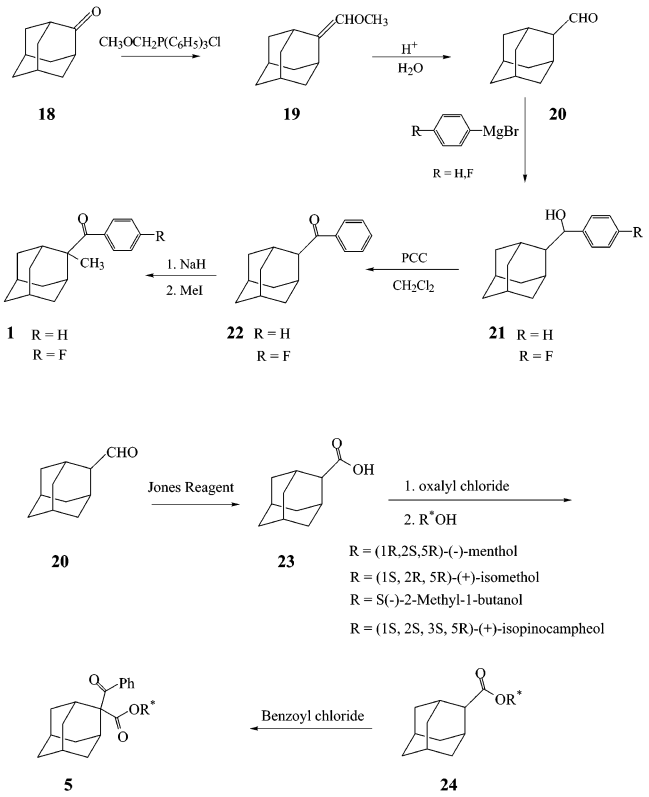
(14) (a) Scheffer, J. R. *Can. J. Chem*. **2001**, *79*, 349. (b) Gamlin, J. N.; Jones, R.; Leibovitch, M.; Patrick, B.; Scheffer, J. R.; Trotter, J. *Acc. Chem. Res*. **1996**, *29*, 203. (c) Leibovitch, M.; Olovsson, G.; Scheffer, J. R.; Trotter, J. *Pure Appl Chem*. **1997**, *69*, 815.

(15) (a) Green, B. S.; Lahav, M.; Rabinovich, D. *Acc. Chem. Res*. **1979**, *12*, 191. (b) Addadi, L.; Lahav, M. *Pure Appl. Chem*. **1979**, *51*, 1269. (c) Sakamoto, M. *Chem. Eur. J*., **1997**, *3*, 684.

(16) (a) Toda, F. *Acc. Chem. Res*. **1995**, *28*, 480. (b) Toda, F.; Tanaka, K.; Miyamoto, H. In *Molecular and Supramolecular Photochemistry*; Ramamurthy, V., Schanze, K., Eds.; Marcell Dekker: New York, 2001; Vol. 8, p 385.

(17) Alberts, A. H. Wynberg, H.; Strating, J. *Synth. Commun*. **1972**, *2*, 79.

SCHEME 9



$(C_6H_5)_3Cl$ (19.3 g, 56.3 mmol). The round-bottomed flask was purged with nitrogen ,and 130 mL of dry diethyl ether was added. The flask was cooled to 0 °C, and 27 mL of *n*-butyllithium (2.5 M solution, 67.2 mmol) was slowly injected by syringe over 5 min. The mixture changes color from yellow to red. The scarlet red suspension was stirred for 1 h under a nitrogen atmosphere. In another round-bottom flask adamantane-2-one **18** was dissolved in 80 mL of dry diethyl ether and added dropwise to the above via a double-ended needle, and the mixture was allowed to stir at room temperature for 15 h. The solution was stirred vigorously while 10 g of anhydrous zinc chloride (73.4 mmol) was added to complex with the suspended triphenylphospine oxide. The ether layer was decanted and evaporated to yield the enol ether **19**, which was hydrolyzed to the aldehyde **20**.

The vinyl ether obtained above was dissolved in 90 mL of diethyl ether. Perchloric acid (70%, 9 mL) and water (5 mL) were added, and the mixture was refluxed for 1 h, after which the mixture was poured into water (100 mL). The organic layer was separated, washed with water, and dried over sodium sulfate. The solvent was evaporated to yield 6.5 g (78% yield) of the aldehyde **20**, which was used without purification in the next reaction with the grignard reagent.

The aldehyde obtained above was reacted with phenylmagnesium bromide to give the corresponding alcohol. In a dry, nitrogen-purged round-bottomed flask, 3.0 g (16.5 mmol) of 2-adamantyl aldehyde was dissolved in 75 mL of THF and cooled in an ice bath. The phenylmagnesium bromide (3.0 M in ether solution, 27 mL, 80 mmol) was added via a syringe over 5 min to the ice-cooled solution of the aldehyde. The mixture was stirred at room temperature for 5 h, after which saturated ammonium chloride was added very carefully. The mixture was extracted with water and dried. The solvent was removed to yield a yellow liquid (4 g, 89% yield) of the alcohol **21**, which was purified by column chromatography (20% ethyl acetate−hexane): ^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.35−7.28 (5H, m), 4.89−4.86 (1H, d), 2.33 (1H, s), 2.08−2.10 (1H, m), 1.93−1.86 (5H, m), 1.81−1.21 (9H, m); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 27.8, 28.0, 28.2, 28.9, 31.8, 32.2, 38.2, 38.9, 39.1, 51.6, 126.8, 127.7, 128.4, 144.1.

The alcohol obtained above was oxidized with PCC to the corresponding ketone.[18] Pyridinium chlorochromate (325 mg, 1.5 mmol) and sodium acetate (35 mg, 0.4 mmol) were suspended in dichloromethane (2 mL). The alcohol 127a (242 mg, 1 mmol) dissolved in 1 mL of CH_2Cl_2 was added in one portion to the magnetically stirred solution of PCC. The solution became briefly homogeneous before depositing the black insoluble reduced reagent. After 2 h, dry ether (10 mL) was added, and the supernatant was decanted from the black gum. The insoluble residue was washed with dry ether (3 × 3 mL), and the combined organic solution was passed through a short pad of Florisil. The solvent was removed to yield the ketone (230 mg, 95% yield). The ketone **22a** was purified by column chromatography (10% ethyl acetate−hexane): ^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.90−7.80 (2H, m), 7.60−7.40 (3H, m), 3.50−3.40 (1H, m), 2.30 (2H, m), 2.10−1.40 (12 H, m); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 27.5, 27.9, 30.3, 32.7, 37.4, 38.8, 52.1, 128.0, 128.4, 132.1, 137.3, 204.0; LRMS (EI) *m/e* (relative intensity) 241 (3.5), 240 (M^+, 20.1), 239 (10.4), 222 (0.9), 197 (1.9), 179 (2.7), 135 (8.0), 120 (2.1), 105 (16.5), 93 (3.5), 79 (3.8), 77 (7.7), 67 (3.6), 41 (2.3); IR cm^{-1} (KBr pellet) 2950, 1676, 1447, 1364, 1221, 973, 766, 698; UV (methanol) 238 (17,800), 278 (sh. 1500), 339 (80) nm.

The ketone obtained above was methylated following the published procedure[6b] to give **1a**: ^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.78−7.64 (2H, m), 7.50−7.30 (3H, m), 2.38 (2H, m), 2.18−2.07 (2H, m), 1.90−1.62 (10 H, m), 1.60 (3H, s); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 23.8, 27.0, 27.2, 32.5, 34.1, 35.0, 38.1, 53.1, 127.8, 127.9, 130.7, 139.2, 210.8; LRMS (EI) *m/e* (relative intensity) 254 (M^+, 3.6), 150 (12.1), 149 (50.0), 148 (9.5), 121 (4.0), 107 (9.4), 105 (9.0), 93 (16.1), 91 (5.5), 81 (11.3), 79 (8.8), 77 (11.6), 67 (8.9), 55 (3.2), 41 (4.2), 32 (4.6); IR cm^{-1} (KBr pellet) 2950, 2913, 2862, 1666, 1596, 1462, 1256, 1214, 1163, 1138, 1104, 1081, 1002, 968, 953, 942, 928, 888, 795, 726, 697; UV (methanol) 239 (9500), 270 (sh. 795), 322 (143) nm.

(b) Synthesis of 1-(4-Flourobenzoyl)-2-methyladamantane (1b). The above compound was synthesized following the procedure published previously.[6b] The NMR and mass spectral data of the intermediates perfectly matched with the literature reports. The final ketone **1b** had the following spectral data, which is in agreement with the literature data: ^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.84−7.70 (2H, m), 7.14−6.99 (2H, m), 2.34 (2H, m), 2.19−2.05 (2H, m), 1.90−1.72 (3H, m), 1.72−1.55 (7H, m), 1.50 (3H, s); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 23.6, 26.9, 27.1, 32.5, 34.2, 34.9, 38.0, 53.0, 114.7 and 115.1 ($^2J_{C-F}$ = 21 Hz), 130.3 and 130.4 ($^3J_{C-F}$ = 8 Hz), 135.0 and 135.0 ($^4J_{C-F}$ = 3 Hz), 161.6 and 166.6 ($^1J_{C-F}$ = 232 Hz), 208.4; LRMS (EI) *m/e* (relative intensity) 273 (0.3), 272 (M^+, 1.5), 150 (14.2), 149 (100.0), 148 (4.6), 123 (7.3), 121 (1.2), 107 (4.0), 95 (5.0), 93 (4.9), 81 (2.4), 79 (2.1), 67 (1.1); IR cm^{-1} (KBr pellet) 2921, 2858, 1668, 1598, 1504, 1454, 1354, 1259, 1226, 1160, 1142, 1103, 1084, 970, 954, 940, 851, 821, 769, 759, 608, 543, 492; UV (methanol) 241 (8900), 333 (70) nm.

(c) Synthesis of Chiral Esters of 2-Benzoyladamantane-2-carboxylic Acid. Esters of (−)-menthol, (+)-isomenthol, *S*(−)-2-methylbutanol, and (+)-isopino-campheol with 2-benzoyladamantane-2-carboxylic acid were synthesized following the general procedure given below for menthyl ester.

Adamantane-2-carboxaldehyde **20** (6.3 g) was dissolved in a 250-mL round-bottomed flask using 70 mL of acetone, and the solution was cooled to 5 °C. A solution consisting of 5.0 g of CrO3, 20 mL of water, and 8 mL of sulfuric acid was added dropwise to the cooled solution until the Jones reagent was in excess. The mixture was allowed to stir at room temperature for 2.5 h, after which the acetone was removed under reduced pressure. Cold water (100 mL) was added, and the mixture was extracted with diethyl ether (3 × 75 mL). The combined ethereal layers were extracted with 1 N NaOH (5 × 50 mL).

(18) Corey, E. J.; Suggs, J. W. *Tetrahedron Lett.* **1975**, *31*, 2647.

After washing with ether, the aqueous layer was acidified with concentrated HCl. The white precipitate was extracted with ether. After washing with water, drying over sodum sulfate, and removal of the solvent in vacuo, adamantane-2-carboxylic acid **23** was left as a white solid (5.9 g, 85%).

A 25-mL round-bottomed flask was flame-dried and allowed to cool with continuous nitrogen flow. The flask was charged with adamantane-2-carboxylic acid **23** (0.36 g, 2.0 mmol) in dry methylene chloride (7 mL). Oxalyl chloride (0.35 mL, 4.0 mmol) was added via syringe. After the mixture stirred for 5 min at room temperature, a catalytic amount of dry dimethylformamide (5 μL) was added. The reaction mixture was allowed to stir for 2.5 h. Excess oxalyl chloride and solvent were removed under reduced pressure. The resulting yellow oil was redissolved in dry methylene chloride (13 mL) and added via syringe (0.31 mL, 2.2 mmol) in methylene chloride, maintained in a nitrogen atmosphere at ice-bath temperature. The mixture was allowed to warm to room temperature and stirred overnight. The solvent was removed in vacuo, and the residue was redissolved in 30 mL of diethyl ether and 15 mL of cold water. The mixture was stirred for a few minutes until all of the solid residue had dissolved. The ethereal layer was separated and washed with 5% hydrochloric acid, a 5% aqueous solution of sodium bicarbonate, water, and a saturated solution of sodium chloride. After drying over anhydrous magnesium sulfate, the solvent was removed in vacuo. The crude product was purified by column chromatography (petroleum ether−diethyl ether, 40:1) to yield **27** as a white solid (508 mg, 1.6 mmol, 80% yield).

Potassium diisopropylamide−lithium *tert*-butoxide (KDA) mixture was prepared following the procedure described by Ramcher and Koople.[19] A flame-dried 50-mL round-bottomed flask equipped with septum and magnetic stirrer was charged with potassium *tert*-butoxide (84 mg, 0.75 mmol) and diisopropylamine (0.11 mL, 0.75 mmol) in dry THF (5 mL) under a nitrogen atmosphere. The flask was cooled to −78 °C, and *n*-butyllithium (0.34 mL, 0.62 mmol, 1.6 M solution in hexane, Aldrich) was added via syringe to form a yellow mixture of potassium diisopropylamide and lithium *tert*-butoxide. The reaction mixture was allowed to stir for 40 min at −78 °C. A solution of ester 130 (161 mg, 0.5 mmol) in THF (5 mL) precooled to −78 °C under a nitrogen atmosphere was added via a double-ended needle. Upon addition the mixture changed from pale to dark yellow in color. The mixture was stirred for 1 h, and benzoyl chloride (0.17 mL, 1.5 mmol) was added via syringe. Stirring was continued for 30 min. The reaction was quenched with 5% HCl, allowed to warm to room temperature, and diluted with diethyl ether. The layers were separated, and the aqueous layer was extracted with diethyl ether. The combined ethereal layers were washed with a saturated solution of sodium carbonate, water, and a saturated solution of sodium chloride. After drying over anhyrous magnesium sulfate the solvent was removed in vacuo to give the crude product that was purified by column chromatography (petroleum ether−diethyl ether, 400:1) to yield the ester **5a** as a viscous oil (171 mg, 0.41 mmol, 81% yield).

Data for ketone 5a: ^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.88−7.86 (2H, m), 7.47−7.43 (1H, m), 7.37 (2H, m), 4.67−4.23 (1H, ddd, J = 10.4 Hz, J = 4.3 Hz), 2.92−2.90 (2H, m), 2.20−2.19 (1H, m), 2.07−2.04 (1H, m), 1.92−1.32 (16H, m), 0.98−0.71 (9H, m), 0.52−0. 51 (3H, d, J = 7 Hz); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 199.7, 171.4, 138.0, 131.8, 128.3, 128.0, 75.2, 65.7, 46.6, 40.1, 37.1, 34.3, 34.2, 34.1, 33.8, 33.8, 32.9, 32.8, 31.3, 26.7, 25.4, 22.7, 21.9, 20.6, 15.4; GC−MS (EI^+) *m/e* (relative intensity) 422 (2, M^+), 284 (2), 211(1), 163(12.9), 162 (100), 134 (3), 118 (2), 105 (30), 83 (8.6), 77 (13), 55 (11), 41 (7.5); IR cm^{-1} (neat) 3066, 2911, 1718, 1681, 1598, 1580, 1456, 1371, 1198, 1097, 1060, 1039, 1010, 982, 950, 914, 845, 821, 800, 783, 773, 698, 679, 647, 627, 470; UV (*n*-pentane) λ_{max} 195 (28000), 240 (8400), 275 (1100), 330 (130) nm.

(19) Ramcher, S.; Koople, G. *J. Org. Chem.* **1978**, *43*, 3794.

Data for ketone 5b: ^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.88−7.86 (2H, m), 7.47−7.43 (1H, m), 7.37−7.33 (2H, m), 5.02−5.01 (1H, m), 2.92−2.90 (2H, m), 2.20−2.19 (1H, m), 1.98−1.96 (1H, m), 1.90−1.23 (16H, m), 0.94−0.71 (9H, m), 0.62−0. 60 (3H, d); GC−MS (EI^+) *m/e* (relative intensity) 422 (2, M^+), 284 (2), 211(1), 163(12.9), 162 (100), 134 (3), 118 (2), 105 (30), 83 (8.6), 77 (13), 55 (11), 41 (7.5); UV (CH_3CN) λ_{max} 205, 245, 280 nm.

Data for ketone 5c: ^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.82−7.80 (2H, m), 7.52−7.50 (1H, m), 7.47−7.50 (2H, m), 4.20−3.88 (2H, ddd), 2.85−2.82 (2H, m), 2.25−2.15 (1H, m), 1.85−1.18 (14H, m), 0.78−0. 68 (6H, m); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 200, 172, 138.0, 132, 128.5, 128.2, 70.2, 66.1, 37.6, 34.6 34.3, 34.0, 33.0, 27.0, 26.8, 26.1, 16.5, 11.2; GC−MS (EI^+) *m/e* (relative intensity) 354 (2, M^+), 211 (1.2), 179(1.3), 162(19.6), 133 (3.1), 105 (100), 77 (24.7), 55 (5), 41 (12); UV (CH_3CN) λ_{max} 200, 235, 265 nm.

Data for ketone 5d: GC-MS (EI^+) *m/e* (relative intensity) 420 (M^+), 285 (12), 284(13.1), 268(10.9), 267 (42), 266 (7.6), 239 (19.5), 136 (20.6), 121 (11.9), 105 (100), 93 (40), 77 (43.5), 55 (23.9), 41 (34.7); UV (CH_3CN) λ_{max} 208, 245, 280, 325 nm.

Procedures for Loading and Photolysis of Adamantane Aryl Ketones 1a, 1b, and 5a−d. Photolysis. All photolyses were performed by using a 450-W medium-pressure mercury lamp placed in a water-cooled Pyrex immersion well (transmits λ > 290 nm). For solution-phase photolysis, the sample was taken in a Pyrex test tube and dissolved in methylene chloride−hexane (1:4) solution. The sample was degassed for 15 min prior to irradiation. A minimum of three samples were irradiated.

Loading, Photolysis of 2-Benzoyl-2-methyladamantane 1a and 1b, and Analysis of Photoproducts. In general samples were prepared under dry conditions. (−)-Ephedrine (30 mg, 182 mmol) was dissolved in a mixture of 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 the adamantyl aryl ketone **1a** (5 mg) in methylene chloride−hexane (1:4). The loading level was maintained at 1 molecule for every supercage for the chiral inductor and 1 molecule for every 10 supercages for the substrate. The slurry was stirred for 12 h, filtered, and washed with hexane (3 × 5 mL). The zeolite complexed with the chiral inductor and the substrate was transferred to a Pyrex test tube and irradiated in hexane for 75 min. The products of the irradiation were extracted with diethyl ether. The ee of the photoproduct of **1a** was determined on the chiral HPLC column OD (Chiralcel). The enantiomers of the product were resolved with hexane−^{i}PrOH (99:1), with a flow rate of 0.5 mL/min, detection at 235 nm. The ee of the photoproduct of **1b** was determined on the chiral GC column Supelco β-dex 350/1701 (10 m, custom-made) (phase:nono-bonded; 50% 2,3-di-*o*-methyl-6-*o*-TBDMS-β-cyclodextrin).

Loading and Photolysis of Chiral Esters of 2-Benzoyladamantane-2-carboxylic Acid and Analysis of Photoproducts. Esters of (−)-menthol, (+)-isomenthol, *S*(−)-2-methylbutanol, and (+)-isopinocampheol with 2-benzoyladamantane-2-carboxylic acid were loaded into MY zeolites and photolyzed as follows, The experiments were carried out under dry irradiation conditions as described below. NaY (300 mg), dried at 500 °C, was taken into 7−8 mL of hexane, and 2 mg of the adamantyl ketoester was added to it. The slurry was stirred for 8 h and filtered, and the zeolite loaded with the compound was vacuum-dried (3 × 10^{-3} Torr) at 65 °C for 6 h and irradiated in a Pyrex test tube in dry hexane (450-W medium-pressure Hg lamp) for 60 min. The products were extracted from the zeolite with diethyl ether.

The de of the photoproduct of **5a** was determined on the GC column SE-30 column (length 30 m, i.d. 0.32 mm, film thickness 0.25 mm). The de of the photoproduct of **5b** was determined using chiralpak AD column with hexane−^{i}PrOH

99:1, flow 0.3 mL/min. The de of the photoproduct of **5c** was determined using chiralpak AD column with hexane−^{i}PrOH 99:1, flow 0.2 mL/min. The de of the photoproduct of **5d** was determined using chiralpak AD column with hexane−^{i}PrOH 99:1, flow 0.3 mL/min.

Characterization of Photoproducts. Cyclobutanols from ketones **1a** and **1b** have been characterized previously, and our spectral data are in agreement with the literature reports.[6] The spectral data of cyclobutanols from ketones **5** were compared with those from ketones **1**. They were identical excepting for additional ^{1}H NMR peaks due to chiral auxiliary. Spectra data from **5a** and **5c** are provided below.

Data for photoproduct of ketone 5a: ^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.88−7.86 (2H, m), 7.49−7.45 (1H, m), 7.36−7.32 (2H, m), 4.60−4.52 (1H, ddd, J = 10.4 Hz, J = 4.3 Hz), 3.45−3.42 (1H, m), 2.90−2.88 (3H, m), 1.92−1.32 (16H, m), 1.0−0.78 (9H, m), 0.63−0. 60 (3H, d); GC−MS (EI$^+$) *m*/*e* (relative intensity) 422 (2.1, M$^+$), 284 (20), 267 (34.4), 266 (10.7), 238-(18.2), 179 (8.6), 162 (16.1), 134 (43), 106 (10.7), 105 (100), 83 (8.6), 77 (13), 55 (37.6), 41 (23.6).

Data for photoproduct of ketone 5c: ^{1}H NMR ($CDCl_3$, 400 MHz) δ 8.1−7.90 (2H, m), 7.58−7.56 (1H, m), 7.54−7.50 (2H, m), 3.4−3.2 (2H, ddd), 3.02−2.98 (1H, m), 2.72−2.62 (2H, m), 2.60−2.58 (1H, m), 2.30−1.22 (13H, m), 0.80−0.76 (3H, m), 0.72−0. 70 (3H, m); GC−MS (EI$^+$) *m*/*e* (relative intensity) 354 (14, M$^+$), 267 (9.7), 266 (17.4), 238 (25), 179 (14), 161 (5.4), 133 (16.3), 105 (100), 91 (20.6), 77 (30.4), 55 (7), 43 (22.8).

Computational Methods Used. Computation on 2-methyl-2-benzoyl adamantane (equilibrium geometry optimization and alkali metal ion Li^+ binding) was carried out using Titan program version 1.0.5 (Schrodinger Inc., Portland, OR) at the RB3LYP level. The 6-31G(d) basis set was used for C, H, O, and Li. Computation on menthyl ester of 2-benzoyladamatane-2-carboxylic acid (geometry optimization and Li^+ cation binding) was done in the Gaussian-98, A.9 program at the B3LYP levl; 6-31G(d) basis set was used for C, H, O, Li.[10] Frequency calculations were done at HF level with 3-21G* basis set for C, H, O, and Li.

Acknowledgment. V.R. thanks the National Science Foundation (CHE-9904187 and CHE-0212042), and J.R.S. thanks the National Sciences and Engineering Research Council of Canada for financial support. Authors thank M. Leibovitch, M. R. Netherton, and A. Zenova for sharing information on synthesis, product characterization, and results of solid-state photolysis of 2-benzoyl adamantanes and related systems described here. V.R. group thanks Drs. J. Chandrasekhar and R. B. Sunoj for their continued help with computational work at Tulane.

Supporting Information Available: Cartesian coordinates of all computed structures. This material is available free of charge via the Internet at http://pubs.acs.org.

JO0260793