Photocycloaddition of Fumaronitrile to Adamantan-2-ones and Modification of Face Selectivity by Inclusion in β-Cyclodextrin† and its Derivatives

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The face selectivity in 5-substituted-adamantan-2-ones (1-Xs) can be dramatically reversed by means of inclusion into β-cyclodextrin (β-CD) and its heptakis(6-O-hydroxypropyl), heptakis(6-O-acetyl), heptakis(2,3,6-tri-O-methyl) and heptakis(2,3,6-tri-O-acetyl) derivatives. The 5-substituents varied from fluoro, chloro, bromo, phenyl to trimethylsilyl, and face selectivities of the oxetane formation have been found to vary with the sizes of 5-substituents and cavities of β-CDs. A 98:2 face selectivity was achieved when 1-SiMe₃ was used as a probe. The effect observed is interpreted by assuming that the carbonyl π-face syn to the bulky 5-substituent is partially blocked by the torus of the host due to complexation of 1-X and CD. Information obtained from 1H NMR titration and X-ray powder diffraction study on the inclusion complex is consistent with the above explanation. X-ray single-crystal structure was used to determine the oxetane structure of anti-2-SiMe₃.

The chemistry of reactive intermediates (guest) within organized and constrained media (host) is of current interest.1 Cyclodextrins (CDs) are cyclic oligosaccharides consisting of six or more α-1,4-linked d-glucose units.2 These bucket-shaped macrocyclic molecules have a cylindrical cavity with a diameter larger than 5 Å and a depth of 7–8 Å. The inside wall of the macrocyclic is comprised of many ether, methylene and methine groups, whereas at both ends of the cavity hydroxy groups are found in a circular arrangement. Cyclodextrins, which possess hydrophobic cavities that are able to include a variety of organic compounds in aqueous solution are one of the most commonly used host systems.1–5 Ramamurthy and Turro and co-workers have exploited the use of CDs as hosts to examine photochemical and photophysical processes that occur in molecules complexed within them and to compare their behaviour in aqueous solution and in the solid state.5–7

Because of the rigid structure of CD molecules, the size and shape of the interior cavity are strictly constrained by the number of constituent glucose units and complex formation is highly stereoselective, that is, guest molecules or groups should fit into the host cavity, even if only partially. Chemical modification of CDs has been extensively studied for the purpose of improving chemical and physical properties, such as solubility, stereoselective complexation, chiral recognition and catalytic powers, etc.1,2

We have previously reported that the photocycloaddition of 5-substituted adamantan-2-ones (1-X, Scheme 1) with fumaronitrile in acetonitrile and in water shows anti-2:syn-2 product ratios varying in the range of 53:47 to 60:40 (Table 1).6b The anti-2-X formed through syn-facel attack of fumaronitrile are the major products in all cases (Scheme 1). Several studies by le Noble and co-workers⁹,10 of a variety of reactions indicate that the reagent prefers to attack the face which is antiperiplanar to the more electron-rich vicinal bonds (syn and anti face preference in 1 when X equals an electron-withdrawing and electron-donating group, respectively, Scheme 2). These results have been reconciled within Cieplak’s transition-state hyperconjugation model.⁸,¹¹ When these reactions were irradiated in aqueous β-CD, reversal of the face selectivity was observed.⁷ The change in face selectivity by complex formation through β-CD was interpreted by assuming that the π-face syn to the bulky 5-substituent of an 1-X-β-CD complex is partially blocked by the torus of the host (Scheme 2).⁷

The effects of CDs on the face selectively are interesting; however, they are modest and are far from the maximum value that can be achieved. We are interested in finding out what will affect the inclusion complex formation of β-CD and thus change the face selectivity in bimolecular reactions. Stimulated by the pioneering work of Breslow and co-workers⁸,¹² to improve acylation rates within flexibly capped cyclodextrins, we used here several modified β-CDs (3a–f) with (i) flexible capping in the primary alcohol sites by hydroxypropyl ether, (ii) ester and ether modifications on both primary and secondary alcohols and selected new 5-substituted adamantan-2-one (1-SiMe₃) in search of better π-facial selectivities and higher solubilities of the.

†β-Cyclodextrin = cyclomaltolheptaose.
† To whom any question related to the X-ray single-crystal structure should be sent.
Table 1  Stereochemical course of the Paterno–Buchi reaction of 5-substituted adamant-2-ones (1-X) with fumaronitrile in aqueous solution containing cyclodextrins as a function of β-CD used and in acetonitrile solution at room temperature

<table>
<thead>
<tr>
<th>Entry</th>
<th>X</th>
<th>CH₃CN</th>
<th>H₂O</th>
<th>3a</th>
<th>3b</th>
<th>3c</th>
<th>3d</th>
<th>3e</th>
<th>3f</th>
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<tbody>
<tr>
<td>1</td>
<td>F</td>
<td>57.43</td>
<td>53.47</td>
<td>45.55</td>
<td>43.57</td>
<td>45.55</td>
<td>41.59</td>
<td>50.50</td>
<td>57.43</td>
</tr>
<tr>
<td>2</td>
<td>Cl</td>
<td>58.42</td>
<td>57.43</td>
<td>26.74</td>
<td>28.72</td>
<td>31.69</td>
<td>24.76</td>
<td>38.62</td>
<td>68.40</td>
</tr>
<tr>
<td>3</td>
<td>Br</td>
<td>59.41</td>
<td>56.44</td>
<td>20.80</td>
<td>22.78</td>
<td>24.76</td>
<td>22.78</td>
<td>29.71</td>
<td>61.39</td>
</tr>
<tr>
<td>4</td>
<td>Ph</td>
<td>65.35</td>
<td>62.38</td>
<td>23.77</td>
<td>31.69</td>
<td>31.69</td>
<td>35.65</td>
<td>12.88</td>
<td>72.25</td>
</tr>
<tr>
<td>5</td>
<td>SiMe₃</td>
<td>59.41</td>
<td>59.41</td>
<td>2.98</td>
<td>24.76</td>
<td>30.70</td>
<td>27.73</td>
<td>49.51</td>
<td>60.40</td>
</tr>
</tbody>
</table>

* Analysis by VPC, error limit ±2%. Yields of 2-X are 70–90% at ≤50% conversion. For studies on CDs: 1 mmol dm⁻³ 1-X, 5 mmol dm⁻³ fumaronitrile in water were used. * 1-X: β-CDs = 1:10, where the plateau value was reported. * Data from ref. 7 are confirmed within ±5% in this work except for the case of 1-Ph and 3a, where ±5% error was found.

Fig. 1  % syn-2 oxetane from anti approach of fumaronitrile to 1-F, 1-Cl, 1-Br and 1-SiMe₃ as a function of β-CD concentration (data for 1-Ph are very similar to those for 1-Br and are omitted for clarity)

Results and Discussion

Results of the Paterno–Buchi reaction of 1-X (where X = F, Cl, Br, Ph and SiMe₃) with fumaronitrile in the presence of β-CD and its derivatives (3a–f) are presented in Table 1. For all studies, excellent yields (70–95%) for oxetanes are obtained, but the reaction was slower in the presence of β-CDs. The effect of CD complexation on the anti: syn ratio is highly dependent on the β-CDs used. For each 1-X, the product anti: syn ratio was dependent on the amount of CD employed; the more extreme values in Table 1 are from the plateau region of the titration curves, such as that shown in Fig. 1. With 1-F and β-CD (3a), there is only a small effect on the face reversal. With 1-Cl and 1-Br and β-CD (3a), syn: anti face selectivities are reversed from those in aqueous solution, ca. 60:40 to 26:74 and 20:80, respectively. The trimethyllyl substituent (1-SiMe₃), which is the largest substituent of the series, shows the most dramatic change in syn: anti face selectivity, from ca. 60:40 to 2:98 when β-CD is used.

For each 1-X, the reversal in face selectivity was smaller when flexibly 12 capped β-CDs such as hydroxypropyl-modified 3b and e were used than when 3a was used (Table 1). The decrease in the reversal of face selectivity in modified β-CDs also showed a strong dependence on the size of the 5-substituent of 1-X. For a small substituent such as F, there is no difference in the selectivity between different β-CDs (entry 1, Table 1). For medium-sized substituents such as Cl and Br, the reverse-face selectivity decreased slightly, from 74 and 80% in β-CD (3a) to 72 and 78% in 3b and to 69 and 76% in 3c (entry 2 and 3, Table 1). For the largest substituent (SiMe₃) of the series, however, a remarkable effect was observed: the oxetane syn-2 (derived from anti-face attack) decreased from 98% in β-CD (3a) to 76% in 3b and to 70% in 3e (entry 5, Table 1). Similar results were found when heptakis(6-O-acetylated) β-CD, 3d, was used. These results indicate that the face selectivities decreased when the primary alcohols of β-CDs were modified to a higher degree of O-hydroxypropyl or O-acetyl substitution. Conceivably, this modification, which leads to much greater solubility in water, may have either of two consequences at the molecular level. First, it may simply extend the depth of the cavity of β-CD. Secondly, if the hydroxypropyl groups turn towards the central axis of the β-CD cavity, they may form an "intrusive floor", closing off the bottom of the cavity, as was envisaged earlier for similar functionalities. 12

In order to test the possible involvement of hydrogen bonding in complex formation between the carbonyl group of 1-X and the secondary alcohol groups of β-CDs, we also used modified β-CDs through methyl ether or acetyl ester substitutions on both the primary and the secondary hydroxy groups (i.e. C₆-H₂O and C₆-H₂O of the glucose units in β-CD). Modifying β-CDs in this way should lead to two possible results: if the cavity of the β-CDs is modified to such an extent that the volume becomes too small to accommodate the large guest molecule, one may see no reversal effect on the face selectivity compared with that in water; on the other hand, if the cavity of modified β-CDs fits the guest molecule better, the face reversal selectivity should be enhanced compared with that in unaltered β-CDs. To test this idea, we employed heptakis(2,3,6-tri-O-methyl)β-CD (3e) and heptakis(2,3,6-tri-O-acetyl)β-CD (3f). The results are also shown in Table 1.

As can be seen from the results using these two β-CDs (3e and...
Fig. 2 % syn-2 oxetane from anti approach of fumaronitrile to 1-SiMe₃ in modified β-CDs (3a-3f) as a function of concentration at room temperature

Fig. 3 ¹H NMR chemical shift differences of β-CD protons as a function of β-CD:1-Ph ratio

Fig. 4 X-Ray powder diffractograms of (a) β-CD, (b) 1-Br, (c) inclusion complex of 1-Br in β-CD and (d) their 1:1 physical mixture

Table 2 300 MHz ¹H NMR chemical shifts of β-CD protons in complexes

<table>
<thead>
<tr>
<th>Compound</th>
<th>1-H</th>
<th>2-H</th>
<th>3-H</th>
<th>4-H</th>
<th>5-H</th>
<th>6-H</th>
</tr>
</thead>
<tbody>
<tr>
<td>β-CD</td>
<td>1523.6</td>
<td>1097.3</td>
<td>1191.6</td>
<td>1077.5</td>
<td>1157.1</td>
<td>1166.4</td>
</tr>
<tr>
<td>β-CD and 1-Ph</td>
<td>1523.6</td>
<td>1097.6</td>
<td>1182.4</td>
<td>1080.2</td>
<td>1145.2</td>
<td>1155.9</td>
</tr>
<tr>
<td>β-CD and 1-Br</td>
<td>1526.8</td>
<td>1101.7</td>
<td>1169.6</td>
<td>1084.6</td>
<td></td>
<td>1169.6</td>
</tr>
</tbody>
</table>

* Chemical shifts are expressed in Hz with reference to external standard Me₂Si in CDCO, sample was in D₂O. 5-SiH was buried under 6-H.

with the concentration of 3a-f in the way expected, given that the solution will approach saturation if the concentration of β-CD is made sufficiently high (e.g. in the manner shown in Figs. 1 and 2).

Evidence for the Formation of β-Cyclodextrin-adamantan-2-one Complexes (β-CD-1-Xs).—The complexes of β-CD with 1-Ph and 1-Br were chosen as model systems for the structural analyses in aqueous solution. The 300 MHz ¹H NMR spectra of aqueous solutions of β-CD and solutions containing various ratios of the host to the guest were recorded. The chemical shifts of β-CD protons in the uncomplexed and in the complexed forms were utilized for drawing conclusions regarding the nature of the complex. Fig. 3 shows a plot of the chemical shift differences for β-CD protons as a function of the ratio of β-CD to 1-Ph. In order to obtain information regarding the relative structures of the complexes of 1-substituted-adamantan-2-ones (1-X), we recorded their ¹H NMR spectra. The results are tabulated in Table 2. From Table 2 it is evident that the cyclodextrin protons 1-, 2- and 4-H are virtually unaffected while the inner protons 3-, 5- and 6-H are shifted upfield to various extents. These upfield shifts of protons provide evidence for the inclusion of the guest molecule into the hydrophobic cavity of β-CD in aqueous solution. In the 1-Ph case, 5-H is shifted upfield to a greater extent (~12.9 Hz) compared with 3-H (~9.2 Hz) and 6-H (~10.5 Hz). The above chemical shift behaviour for the cyclodextrin protons definitely establishes that the phenyl ring of 1-Ph is positioned within the cyclodextrin cavity. Similar results in ¹H NMR spectroscopy in the studies of β-CD complexes with dibenzyl ketone were observed. Since a recent report from MM2 calculations and NOE (¹H NMR) experiments by Jaime et al. also supports the 1:1 inclusion complex of 1-bromoadamantane and β-CD. Their results also predict that the bromine atom points into the β-CD cavity.

Complexes formed between 1-Xs and 3a-f most probably have 1:1 stoichiometries, as found in several instances by X-ray crystallography. Since the complexes of 1-Xs with β-cyclodextrin did not yield suitable single crystals for X-ray crystallographic studies, no such investigation was pursued. Formation of solid inclusion complexes between cyclodextrin...
and 1-Br was evident from X-ray powder photographs. The X-ray powder pattern of the precipitated solid differed from those of the guest and the host or their 1:1 physical mixture (Fig. 4).

Stability and Possible Structure of the Complexes.—If the relative ratio of the product is employed as a binding parameter, binding constants for these complexes of β-CD can be obtained.‡ Binding constants of 1-Xs in β-CD have been determined previously to be (8.7 ± 3.5) × 10² (for 1-F), (8.7 ± 2.6) × 10² (for 1-Cl), (8.4 ± 3.5) × 10² (for 1-Br) and (1.33 ± 0.39) × 10³ dm³ mol⁻¹ (for 1-Ph). The binding constant for the newly added guest, 1-SiMe₃, was determined to be (1.27 ± 0.18) × 10³ dm³ mol⁻¹. Note that the magnitudes of the reversal selectivities described here do not parallel the stabilities of the CD–1-X complexes, but can be explained on the basis of the stereochemistry of the CD–1-X complexes (Scheme 3).²b,c,7 Substituents of our probe molecules (1-Xs) may be divided into three categories: spherical ball (e.g. halogen atoms), planar structure (e.g. phenyl group) and three dimensional tetrahedron (SiMe₃ or tert-butyl), and they probably will have different stereo requirements in the cavity of β-CDs. In β-CD solutions when the percentage syn-2-X was plotted vs. the van der Waals radii of the 5-substituents of 1-X for the same group of elements (e.g. F, Cl and Br),¹¹ a clear linear correlation was observed: the larger the substituent the higher the anti face selectivity (Fig. 5).

Our interpretation for results of photocycloaddition reactions of 1-Xs in β-CDs (3a-f) is that β-CD or its derivative complexes the 1-Xs (with the bulkier X) so that the normally preferred carbonyl face is protected by the torus of the host (complex B, Scheme 3). With relatively 'large' substituents of 1-X (e.g. 1-SiMe₃), complex B should, in fact, be favoured in the equilibrium between complex A and B;¹⁶ complex A should increase in importance when the 5-substituents are 'small' (e.g. 1-F). Besides varying sizes of guest molecules (1-Xs), we also varied the cavity depths (narrow end) and its wide end (C-2 and -3 hydroxy group) through chemical modification of the host molecule.

Modifying a β-CD’s primary alcohol groups by hydroxypropyl or methyl ether should form an intrusive floor in the narrow-end of the β-CD cavity. The crystal structure of heptakis(2,3,6-tri-O-methyl)-β-CD (3e) with various guests has been reported in which five of the seven O(6)-methyl groups are inclined toward the inside of the cavity and make the O(6) end of the cavity narrower and capped (e.g. 3b-3e). If complex B in Scheme 3 is really the inclusion complex that determines the face attack, then a flexibly capped β-CD should not affect the inclusion of 'small' substituents (such as 1-F and 1-Cl) but should obstruct the full inclusion of 'large' substituents (such as 1-Br and 1-SiMe₃). The results in Table 1 are fully consistent with this explanation. What needs to be explained is why 1-Ph in β-CD (3e) did not show the expected loss of anti-attack preference and why in fact it was highly enhanced (entry 4, Table 1). From the ¹H NMR study (see Supplementary Material), we speculate that the planar phenyl substituent in 1-Ph may still be able to penetrate deep into the cavity and is held tightly by the flexible methoxy groups, thus showing a better anti-face selectivity (88:12).

In their study of hydrolysis rates within β-CD complexes, Breslow et al. invoked similar orientations in order to explain the observed acceleration rates of (3-tert-butyl-1-adamantyl) propiolate. Improvement of the acylation rates within CD complexes was achieved by 'capping' the CD and by adjusting the shape of the substrate. The current results for the modified β-CDs further support the inclusion complex model proposed in Schemes 2 and 3 and owing to this complexation, the originally favoured syn-face of the carbonyl group is blocked by the torus of CDs and leads to a completely reversed product selectivity. Note that two other recent reports strongly support the idea of 'using inclusion complexes of CDs as a steric shield' in controlling bimolecular reactions. In the reduction of norborn-7-ones, Mehta et al. found that the face selectivity can be altered or reversed by inclusion into β-CD similar to those studied here. Trost and Van Vranken also used this idea in the osmium-catalysed oxidation of a benzyl oxazoline ether, in which the benzyl group was placed in the cavity of the cyclo-dextrins, thereby introducing the latter as a shield for the convex face. The selectivity of their reactions was modest and could probably be enhanced by using the methodology applied here.

One may question whether the modification of face selectivity discussed above is really due to the formation of inclusion complexes (such as that shown in Scheme 3) or whether it may just be a solvent-polarity effect. Photocycloaddition reactions of 1-Br with fumaronitrile in solvents of different relative permittivity were carried out and the results are presented in Table 3. Solvent polarities were varied from very polar, e.g. water (ε = 78), acetonitrile (ε = 36), methanol (ε = 33) and dichloromethane (ε = 8.9) to non-polar solvents, e.g. benzene (ε = 2.3) and hexane (ε = 1.7). Within the range of experi-

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‡ In general, one might use the differences in optical density or the differences in fluorescence intensity to determine the binding constants. The UV-absorption experiment was performed, but the small difference in optical density at the highest CD concentration studied (ca. 15 mmol dm⁻³ in H₂O) made estimating the binding constant very difficult. The fluorescence experiment was hampered by the impurities in the commercially available β-CD.

Fig. 5 % anti-face attack in the reaction of 1-Xs with fumaronitrile in β-CD solution as a function of the size of the 5-substituents of 1-Xs (only same group of elements fit this line)
Table 3 Face selectivities in the Paterno–Büchi reaction of 1-Br with fumaronitrile in solvents of different polarities at room temperature

<table>
<thead>
<tr>
<th>Solvents</th>
<th>Relative permittivity</th>
<th>trans-Dicyanooxetane, a</th>
<th>anti-2-Br:syn-2-Br</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂O</td>
<td>78</td>
<td>57:43</td>
<td></td>
</tr>
<tr>
<td>CH₃CN</td>
<td>36</td>
<td>59:41</td>
<td></td>
</tr>
<tr>
<td>MeOH</td>
<td>32.7</td>
<td>60:40</td>
<td></td>
</tr>
<tr>
<td>CH₂Cl₂</td>
<td>8.9</td>
<td>58:42</td>
<td></td>
</tr>
<tr>
<td>Benzene</td>
<td>2.3</td>
<td>61:39</td>
<td></td>
</tr>
<tr>
<td>Hexane</td>
<td>1.7</td>
<td>60:40</td>
<td></td>
</tr>
</tbody>
</table>

* Data of solvent relative permittivities were from C. Reichardt, Solvents and Solvent Effects in Organic Chemistry, 2nd ed. VCH, New York, 1990. * Analysis by GC, error limits ± 2%. Yields of 2-Br are ≥90% at low (<20%) conversion. The ratios stay constant during the long irradiation periods.

Fig. 6 ORTEP drawing of structure anti-2-SiMe₃

Experimental

NMR spectra were recorded on either a Varian Unity-300 or 400 spectrometer with Me₃Si in CDCl₃ as an internal or external standard. Powder diffractograms were recorded on a MacScience MXP3 X-ray powder diffractometer equipped with Cu-Kα radiation. Gas chromatography was carried out on a Hewlett-Packard 5890 instrument equipped with an FID detector using either a 25 m HP-1 cross-linked methyl silicone column or a Carbowax column at 200 °C.

Materials.—Fumaronitrile (Merck), adamantant-2-one (Aldrich) and β-CDs (Aldrich or Merck) were used as received. Doubly distilled water was used for all the experiments and organic solvents were distilled twice prior to use. Tetraakis(6-O-hydroxypropyl)-β-CD (3b) and heptakis(6-O-hydroxypropyl)-β-CD (3c) are not pure compounds, being available at different degrees of substitution. We used the materials provided by Amaizo which have averaged molecular weight of 1388 for 3b and 1541 for 3c, respectively, corresponding to the replacement of about 3.5 and 7 primary hydroxy groups of β-CD by hydroxypropyl groups. Heptakis(2,3,6-O-methyl)-β-CD (3e) and heptakis(2,3,6-O-acetyl)-β-CD (3f) were purchased from Materials. —Fumaronitrile (Merck), adamantant-2-one (Aldrich) and β-CDs (Aldrich or Merck) were used as received. Doubly distilled water was used for all the experiments and organic solvents were distilled twice prior to use. Tetraakis(6-O-hydroxypropyl)-β-CD (3b) and heptakis(6-O-hydroxypropyl)-β-CD (3c) are not pure compounds, being available at different degrees of substitution. We used the materials provided by Amaizo which have averaged molecular weight of 1388 for 3b and 1541 for 3c, respectively, corresponding to the replacement of about 3.5 and 7 primary hydroxy groups of β-CD by hydroxypropyl groups. Heptakis(2,3,6-O-methyl)-β-CD (3e) and heptakis(2,3,6-O-acetyl)-β-CD (3f) were purchased from.

** For example, at room temperature the modified β-CDs 3b and 3c have at least 1 mol dm⁻³ solubilities in water compared with ca. 18 mmol dm⁻³ for β-CD itself. The 2,3,6-O-methyl derivative of β-CD (3e) is not only soluble in organic solvents, but is also at 10 times more soluble in water than is the parent β-CD.

Conclusions

The results presented here show that (i) there is a close relationship between the van der Waals radii of 1-Xs and the syn-oxetane selectivity in the inclusion complexes, (ii) a much higher face selectivity is achieved from size changes of guest molecules and host molecules, (iii) methylation or hydroxypropylation in the primary alcohols of β-CD forms a flexible floor at the narrow-end, which hampers the inclusion of a large substituent, but not the small substituent, (iv) the change in face selectivity observed is not due to solvent-polarity effects. The present results, by modification of β-CD and by tuning the sizes of the substrates and hosts, have demonstrated that the attack of fumaronitrile can be directed towards the exposed anti face of the carbonyl group through complexation with β-CDs (Scheme 3), and the inclusion of 5-substituents of 1-Xs were from the wider secondary side of the CD cavities. Moreover, the depth of penetration of the guests into the cavity must be such that they barely encounter the hydroxypropyl (or acetyl) groups on the distal, primary side of β-CDs (3b, c and d). Thus, anti-face selectivity decreased for large substituents owing to shallower binding and less protection of the syn-n face of the carbonyl group (Scheme 4). Since these modified β-CDs have much better solubility** in water and other organic solvents than β-CD itself does, the application of CDs for traffic control clearly has synthetic potential. We are continuing to explore the interaction of CDs with bound reactive intermediates and are using CDs to control the regio- and stereo-chemistry of other bimolecular reactions.
Cyclo lab (Hungary) and were used as received. The synthesis of 5-trimethylsilyladamantan-2-one (1-SiMe3), 5-phenyladamantan-2-one (1-Ph), 5-chloro-, 5-bromo- and 5-fluoroadamantan-2-ones have all been described elsewhere. All compounds mentioned in this paper have been completely characterized by NMR analysis and most of them have been reported previously.\(^8\)

anti-5-Trimethylsilylspiro[adamantan-2,2'-oxetane]-trans-3',4',4'-dicarbonyl-

anti-2-SiMe3.: White solid (mp 154°C). \(\delta_{H}(300 MHz, CDCl3) 5.12(1H, d, J=5.86 Hz), 3.67(1H, d, J=5.86 Hz), 2.39(1H, br s), 2.32(1H, br s), 1.90-2.15(2H, m), 1.58-1.78(9H, m)\) and \(-0.086(9H, s)\). \(\delta_{C}(75.4 MHz, CDCl3) = 51.51(1H, d, J=5.86 Hz), 3.67(1H, d, J=5.86 Hz), 2.39(1H, br s), 2.32(1H, br s), 1.90-2.15(2H, m), 1.58-1.78(9H, m)\) and \(-0.086(9H, s)\). In the NMR spectra, the singlet at \(-0.086 ppm\) is assigned to the trimethylsilyl group.

X-Ray Structure Analysis of anti-2-SiMe3. - (See Fig. 6 for ORTEP drawing). Mp 154°C, was crystallized from 10% ethyl acetate in hexane. Its structure was determined by means of single-crystal X-ray analysis on a Rigaku AFC66 diffractometer with a graphite monochromated Cu-K\(\alpha\) radiation at 296 ± 1 K, with an o20 type scan at a speed of 16 deg min\(^{-1}\) (in o). The crystals are primitive monoclinic, with space group \(P2_1/c\) (No. 14) and unit cell dimensions \(a = 14.488(3), b = 9.1729(3), c = 13.253(3), \beta = 91.482(5)\). The atomic positions were obtained by a direct method using a Varian Unity-300 spectrometer equipped with a UNIX computer system. Water elimination program (WEFT)\(^2\) provided by the instrument was used to approximate the structure. The structure was refined by the least-squares method with \(\omega = 1/[\sigma^2(F o)]\) to final \(R\) values of 0.079 and \(R_p = 0.082\).\(^6\)

syn-2-SiMe3.: White solid (mp 170°C). \(\delta_{H}(300 MHz, CDCl3) 5.11(1H, J=5.86 Hz), 3.67(1H, d, J=5.86 Hz), 2.38(1H, br s), 2.32(1H, br s), 1.86-1.87(1H, m), 1.82-1.85(4H, m), 1.50-1.69(6H, m)\) and \(-0.10(9H, s)\). In the NMR spectra, the singlet at \(-0.10 ppm\) is assigned to the trimethylsilyl group.

Photocyclodimerization.-1-Xs (1 or 5 mmol dm\(^{-3}\)) were added to water or to aqueous solutions of varying amounts of CDs and ultrasonically agitated for 50 min to promote the dissolution of ketones. An excess of furanomir nitile (100 mmol dm\(^{-3}\)) was then added to 20 cm\(^3\) of the solution and dissolved by magnetic stirring for 1 h. Each sample (20 cm\(^3\)) was allowed to equilibrate for 2 h at 25°C, after which it was irradiated at ambient temperature in stopped Pyrex tubes for 12 h by the output from a high pressure Xe-Hg lamp (1 kW) with a K\textsubscript{2}CrO\textsubscript{4} filter solution. The solutions were clear except for those of 1-Ph and 1-SiMe\(_3\), in which cloudy solutions were irradiated. The solutions were then extracted with ether (3 \(\times\) 20 cm\(^3\)) and dried (Na\textsubscript{2}SO\textsubscript{4}), the ether was removed under reduced pressure to give a white solid. Under these conditions, the conversion was 10-80% and the yield of oxetanes was 70-95%. The product ratios were determined by GC. At low conversion only trans-dicyanooxetanes were formed; cis-dicyanooxetanes were obtained only after the cis-trans isomerization of furanominitile has set in.\(^8\) As in acetonitrile, the aqueous reactions exhibit a clear preference for the syn approach to form the anti-oxetane (Table 1).

Powder Diffraction of Solid Cyclodextrin Complexes.—To an aqueous solution of \(\beta\)-CD (0.05 mol dm\(^{-3}\), 10 cm\(^3\)) were added equimolar amounts of the guest ketones 1-Xs and the solutions were heated to 40°C and allowed to cool to room temperature while stirring overnight. The white precipitate thus obtained was filtered, washed with cold water several times and dried in vacuo at room temp. for 1 h. The X-ray powder diffraagrams of \(\beta\)-CD and complexes of \(\beta\)-CD and ketones 1-X (where X = Br and Ph) were recorded. The powder photographs of the complexes were different from that of \(\beta\)-CD or a 1:1 physical mixture of \(\beta\)-CD and ketones. On this basis it was concluded that inclusion complexes between \(\beta\)-CD and the guest ketones 1-Xs have been formed.

NMR Studies. Sample Preparation.—Solutions containing different proportions of guest-to-host were prepared by stirring 4-5 mg of the guest molecule 1-X with 0.4, 0.8, 1.0, 1.5, 2 and 3 equiv. \(\beta\)-CD solution (15 mmol dm\(^{-3}\) stock solution in \(D_2O\) in 1 cm\(^3\) \(D_2O\) for ca. 1 h before measurement. The NMR spectra of all the \(\beta\)-CD complexes, \(\beta\)-CD and 1-Xs in \(D_2O\) and \(CDCl_3\) with a coaxial external standard (SiMe\(_4\) in \(CDCl_3\)) were recorded with a Varian Unity-300 spectrometer equipped with a UNIX computer system. Water elimination program (WEFT)\(^2\) provided by the instrument was used to suppress the water peak. Temperature was set to be 24.0 ± 0.5°C for all measurements. The guest-induced shifts in the \(\beta\)-CD protons were computed by comparing the above spectra with that of pure \(\beta\)-CD.

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