Cis–Trans Photoisomerization in a Tri-*o*-thymotide Clathrate. Crystal Structure of Tri-*o*-thymotide Clathrates of *cis*- and *trans*-Stilbene

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Abstract: New clathrate inclusion complexes of tri-*o*-thymotide (TOT) which contain *cis*-stilbene or *trans*-stilbene have been prepared and characterized; both crystallize in the triclinic space group $P\bar{1}$ and have closely similar cell constants. Each unit cell of the *trans*-stilbene·TOT complex contains four TOT molecules and two stilbene molecules; the stilbenes lie on crystallographic centers of symmetry within two crystallographically independent sausage-like channels. The *cis*-stilbene·TOT complex contains partially empty channels, the TOT:stilbene ratio being approximately 2.5:1, and the disordered guest molecules could not be located. On irradiation through Pyrex, the *cis*-stilbene·TOT clathrate is transformed to *trans*-stilbene·TOT clathrate; phenanthrene is also formed. The experimental results are consistent with a pathway involving photoisomerization of the *cis*-stilbene *within* the clathrate inclusion complex. The photoreactivity of the *cis*-stilbene complex, and stability of the *trans*-stilbene clathrate, may be ascribed to the disorder, larger volume, and higher energy of the cis species, but we ascribe particular importance to the coincidence or noncoincidence of molecular symmetry and cavity symmetry. The centrosymmetric cavity appears to stabilize centrosymmetric molecules and favor reaction pathways from noncentrosymmetric reactants to centrosymmetric products. The cis and trans isomers of methyl cinnamate also form triclinic TOT clathrate crystals, but here, where neither reactant nor product can achieve the symmetry of the cavity, irradiation yields approximately equal amounts of cis and trans isomer starting from either pure *cis*- or pure *trans*-cinnamate clathrate.

Clathrate inclusion compounds[2] have attracted considerable interest since, unlike ordinary compounds, the clathrates comprise two different molecular species, guest and host, which associate to form stable crystalline compounds in which the guests are enclosed by channels or cages comprised of host molecules; there are no covalent or ionic bonds linking the two dissimilar species. From the point of view of chemical reactions in the medium of the crystalline state,[3] clathrates may hold particular promise since two or more species differing in shape, polarity, and functionality may be brought together to form a solid phase. This "crystal engineering" concept allows one to form and conveniently handle potentially reactive crystals which may be comprised of solids as well as components which would normally be liquids or gases at room temperature. In addition, intermolecular (and perhaps intramolecular) nonbonded interactions are drastically changed on enclathration and these may be expected to alter reactivity. Several solid-state chemical reactions of clathrate inclusion compounds have been reported,[4] but few of the many possible clathrate hosts have been studied, and the scope of chemical reactions investigated thus far remains very limited.

We have chosen to investigate the chemical and crystallographic properties of the clathrates formed with tri-*o*-thymotide (TOT); see Figure 1. Although first prepared in 1865,[5a] the structure of TOT was only established in 1952 by Baker and co-workers,[5b] who first discovered that TOT was different from closely related compounds[6] in that on crystallization from organic solvents it formed stable clathrate inclusion compounds. The structures and properties of these clathrates were first provided by Powell and co-workers,[7] who extensively investigated a series of complexes. More detailed descriptions have become available recently as a result of the crystallographic studies on cage-type clathrates[8,9] and a channel-type clathrate of TOT.[9] The structure of solvent-free TOT has also been reported.[9,10]

In addition to the number and variety of compounds which are included by TOT, another impetus for our choice of TOT clathrates was the early observation of Powell that the TOT clathrates crystallize in chiral structures and thus represent an interesting example of spontaneous resolution. Partial resolution of molecules which lack the usual functional groups required for diastereomeric compound formation has been reported,[11] and one is prompted to consider the possibility of asymmetric synthesis via reactions of prochiral guest molecules incorporated in chiral crystals of TOT clathrates.[12] However, as will be seen shortly, the compounds described herein actually represent examples of TOT clathrates which crystallize in *achiral*, centrosymmetric crystal structures.[13]

While studying the scope of molecular variation which may be accommodated in TOT host crystals, it was found that *cis*-stilbene and *trans*-stilbene are readily enclathrated. Exposure of crystals of *cis*-stilbene·TOT clathrate to UV light transformed them to *trans*-stilbene·TOT crystals, and the reaction, which represents the first reported chemical transformation in a TOT clathrate as well as the first photoisomerization of a clathrate inclusion compound, was then studied in greater detail.

Experimental Section

Tri-*o*-thymotide (TOT) was synthesized from *o*-thymotic acid by treatment with $POCl_3$ in boiling xylene[5b] and purified by chromatography on silica gel.[14] Final purification was achieved by crystallization from chloroform–cyclohexane, which afforded large, colorless crystals of clathrate. Solvent-free material was obtained by warming to 130 °C at 0.2 mm for 24 h and recrystallizing from methanol.

X-ray powder diffraction spectra were taken with a Philips powder diffractometer using Cu $K\alpha$ ($\lambda = 1.5418$ Å) radiation. VPC analyses were performed on a Varian Aerograph Autoprep Model A 700 instrument using a ⅛ in. × 2 m 10% SE-30 on Chromosorb W 30/60 column. For analysis of the stilbenes the column was maintained at 120°C until *cis*-stilbene had emerged and was then temperature programmed from 120 to 270 °C at 20 °C/min; *trans*-stilbene appeared at 135 °C, TOT at 270 °C, and phenanthrene at 145 °C (injector, 230 °C; detector, 340 °C). For analysis of the methyl cinnamates, the column was maintained at 100 °C until *cis*- and then *trans*-methyl cinnamate emerged and was then programmed from 100 to 270 °C at a rate of 20 °C/min (injector 220 °C; detector 280 °C). In all cases, the flame ionization detector response was calibrated with mixtures of known composition. Peak areas were estimated by the cut-and-weigh method or with a Spectra Physics Minigrator.

Irradiations were performed with Westinghouse 40 W sunlamps; the samples were exposed, through Pyrex, at a distance of 10 cm from

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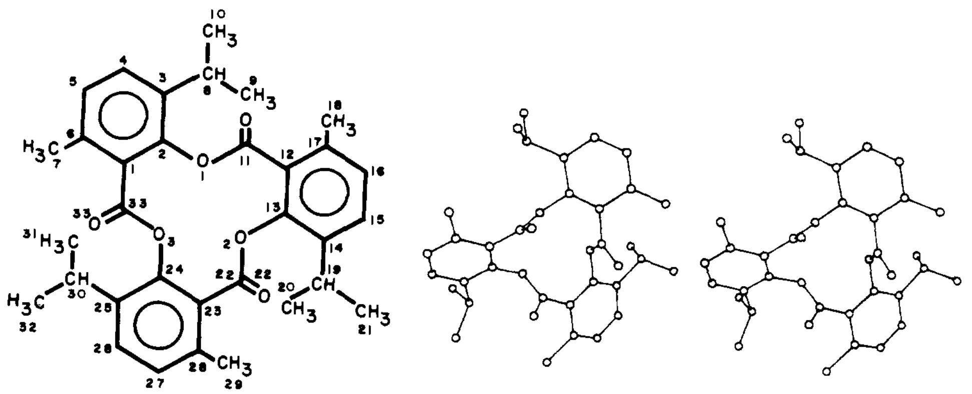

Figure 1. Structure of tri-*o*-thymotide (TOT) molecule showing the atomic numbering used in the crystal structure analysis. The stereodrawing on the right[10] illustrates the propeller-like conformation of TOT in the solid.

a bank of four lamps. The lower temperature irradiations were accomplished by placing the entire apparatus in a cold room having the indicated temperature. Melting points were measured on a Fisher-Johns apparatus and are uncorrected. NMR spectra were recorded on Varian A-60 and Bruker HFX-10 spectrometers in deuteriochloroform using tetramethylsilane as internal standard. The host-guest ratios were established by VPC analysis, from density measurements and cell constants of the crystals, or by integration of the NMR signals in a solution prepared from a polycrystalline sample.

Preparation of Clathrates. *cis*-Stilbene·TOT Clathrate. A saturated solution of TOT in methanol was prepared by dissolving 150 mg of solvent-free TOT in 50 mL of boiling absolute methanol. After cooling to room temperature the solution was filtered into a 100-mL beaker containing 205 mg (fourfold molar excess) of *cis*-stilbene; the solution was stirred and then allowed to stand in the dark. After 3 days the colorless crystals which had formed were filtered and washed with methanol and several drops of acetone, mp 178-180 °C, *cis*-stilbene:TOT ratio ca. 1:2.5 (the values varied from 1:2.3 to 1:3.2 for different crystals and samples).

***trans*-Stilbene·TOT Clathrate.** The clathrate crystals were prepared as described for the cis isomer, except that the methanolic solutions of *trans*-stilbene and TOT were warmed to boiling before being set aside for crystallization, mp 178-180 °C, *trans*-stilbene:TOT ratio exactly 1:2.

Methyl *trans*-cinnamate·TOT clathrate was prepared in the same way, cinnamate:TOT ratio 1:2. The crystals, mp 178-180 °C, belong to space group $P\bar{1}$ (or $P1$) and have the following cell constants: a = 24.19 Å, b = 11.51 Å, c = 13.04 Å, α = 91.3°, β = 96.6°, γ = 101.8°, $Z = 2\ (C_6H_5CH{=}CHCO_2CH_3{\cdot}2TOT)$, d_{calcd} = 1.14 g/cm^3, d_{meas} = 1.11 g/cm^3.

Methyl *cis*-cinnamate·TOT clathrate crystals were prepared in the same way, mp 178-180 °C, cinnamate:TOT ratio 1:2. The crystals, space group $P\bar{1}$ (or $P1$), have the following unit cell dimensions: a = 25.0 Å, b = 11.3 Å, c = 13.0 Å, α = 92.0°, β = 94.0°, γ = 102°, $Z = 2\ (C_6H_5CH{=}CHCO_2CH_3{\cdot}2TOT)$, d_{calcd} = 1.13 g/cm^3, d_{meas} = 1.08 g/cm^3.

Iodine·TOT clathrate was reported previously.[7b] Iodine (200 mg) was added to a hot solution of TOT (30 mg) in methanol (10 mL), and the solution was placed in a Dewar containing water previously heated to 65 °C. The Dewar was sealed and allowed to stand for 2 days. There resulted reddish-black crystals.

When methanol solutions of TOT and potential guest species were evaporated, as described above, crystals of unsolvated TOT occasionally deposited from the solutions; *trans*-stilbene invariably afforded clathrate crystals, *cis*-stilbene gave clathrate crystals with somewhat less probability, and the methyl esters of cinnamic acid were most problematic. When 1:1 mixtures of *cis*- and *trans*-stilbene were subject to TOT enclathration, the resulting crystals contained a trans:cis isomer ratio of 19:1.

Crystallographic Studies on the Stilbene Clathrates. Preliminary data, collected on film, show the triclinic space group $P\bar{1}$ or $P1$. Accurate cell dimensions were determined with an Enraf-Nonius CAD-4 automated diffractometer using a graphite monochromator and Cu Kα radiation (λ = 1.5418 Å). All data were collected with the ω-2θ scan technique up to θ = 45° for the *cis*-stilbene clathrate and up to θ = 50° for the *trans*-stilbene clathrate. Three standard reflections, measured after every 100 reflections indicated that no change occurred during the data collection. For the *cis*-stilbene clathrate, 5285 independent reflections were collected, 1541 of which were considered as unobserved ($I \leq 2\sigma I$); for the *trans*-stilbene clathrate, 7767 independent reflections were collected and 1344 of these were considered unobserved. The crystal data for the two clathrates are presented in Table I. Another unit cell has been given in a preliminary report.[15] Owing to the near coincidence of $|\cos \beta|$ and $a/2c$ that unit cell has axes of similar length to those of Table I; the transformation for converting the latter is

Table I. Crystal Data of the *cis*- and *trans*-Stilbene·Tri-*o*-thymotide (TOT) Clathrates

	cis-stilbene·TOT	*trans*-stilbene·TOT
a, Å	11.323	11.639
b, Å	13.161	13.027
c, Å	24.862	24.409
α, deg	95.52	96.05
β, deg	103.70	103.21
γ, deg	86.39	84.81
V, Å^3	3580	3574
$F(000)$	1324	1324
μ(Cu Kα)	7.54	7.54
ρ_m, g cm^{-3}	1.146	1.150
ρ_c, g cm^{-3}	1.150	1.152
Z	2	2

$$\begin{matrix} +1 & 0 & 0 \\ 0 & -1 & 0 \\ -1 & 0 & -1 \end{matrix}$$

The *trans*-stilbene·TOT structure was solved using the rotation function[16] and refined in space group $P\bar{1}$. The *trans*-stilbene molecules appear clearly on the Fourier maps. After isotropic refinement, an R factor of 0.131 was obtained. The refinement of the *cis*-stilbene·TOT structure was attempted starting from the positions of the TOT molecules given by the rotation function. During the refinement procedure, peaks corresponding to the *cis*-stilbene guests appeared on the Fourier maps when the R factor reached a value of 0.21; however, the *cis*-stilbene molecules as such could not be seen.

The atomic coordinates for the *trans*-stilbene clathrate are presented in Table II. The numbering of atoms of TOT is the same as that used in previous studies[10] and is shown in Figure 1; the numbering of the two independent half-*trans*-stilbene molecules is shown in Figure 2. The temperature factors of the atoms of the TOT molecules are normal and those of the *trans*-stilbene molecule are slightly larger than normal. The atomic coordinates of the TOT molecules in the *cis*-stilbene·TOT clathrate differ very little from those of the *trans*-stilbene clathrate and are listed along with the supplementary material. The deposited supplementary material includes the observed and calculated structure factors for the *trans*-stilbene·TOT clathrate, the thermal parameters of the atoms in the *trans*-stilbene·TOT clathrate, and the atomic coordinates and thermal parameters of TOT in the *cis*-stilbene clathrate.

Table II. Atomic Coordinates in *trans*-Stilbene·TOT Clathrate (×10^4), with Standard Deviations (×10^4)[a]

1C^{T}(1)	9744 (14)	4647 (12)	9828 (6)	2C^{T}(1)	5096 (29)	5395 (30)	4886 (18)
1C^{T}(2)	8400 (12)	4631 (11)	9696 (6)	2C^{T}(2)	4657 (13)	6440 (12)	5146 (6)
1C^{T}(3)	7972 (13)	3818 (12)	9287 (6)	2C^{T}(3)	5013 (13)	7157 (13)	4847 (6)
1C^{T}(4)	6708 (15)	3768 (14)	9111 (7)	2C^{T}(4)	4806 (14)	8234 (14)	4967 (7)
1C^{T}(5)	5931 (15)	4470 (15)	9333 (7)	2C^{T}(5)	4190 (14)	8604 (13)	5392 (7)
1C^{T}(6)	6411 (16)	5237 (14)	9769 (7)	2C^{T}(6)	3854 (15)	7896 (15)	5694 (7)
1C^{T}(7)	7653 (15)	5313 (13)	9944 (7)	2C^{T}(7)	4083 (14)	6818 (14)	5588 (7)
10(1)	3057 (5)	5860 (5)	7525 (2)	20(1)	−0469 (5)	−0.421 (5)	8301 (3)
10(2)	2269 (5)	4142 (5)	6708 (2)	20(2)	9568 (6)	1248 (5)	7614 (3)
10(3)	0773 (5)	5936 (5)	6723 (2)	20(3)	1366 (5)	0990 (5)	8590 (3)
10(11)	4409 (7)	6220 (7)	7068 (4)	20 (11)	7966 (8)	0378 (7)	8603 (4)
10(22)	2718 (6)	4206 (6)	5867 (3)	20 (22)	8681 (7)	2674 (7)	7984 (4)
10(33)	1496 (7)	6845 (6)	6174 (3)	20 (33)	0722 (8)	1862 (7)	9319 (4)
1C(1)	1884 (8)	7344 (7)	7166 (4)	2C(1)	0783 (8)	−0008 (8)	9214 (4)
1C(2)	2692 (8)	6916 (7)	7594 (4)	2C(2)	0073 (8)	−0689 (8)	8847 (4)
1C(3)	3148 (9)	7485 (9)	8113 (4)	2C(3)	−0081 (9)	−1688 (8)	8971 (4)
1C(4)	2700 (10)	8535 (10)	8174 (5)	2C(4)	0549 (10)	−1954 (9)	9506 (5)
1C(5)	1907 (10)	8966 (10)	7740 (5)	2C(5)	1283 (10)	−1277 (9)	9878 (5)
1C(6)	1479 (9)	8397 (9)	7224 (5)	2C(6)	1420 (9)	−0288 (8)	9744 (4)
1C(7)	0540 (11)	8889 (10)	6766 (5)	2C(7)	2257 (10)	0439 (10)	10 160 (5)
1C(8)	4021 (10)	6972 (9)	8584 (5)	2C(8)	−0876 (10)	−2412 (10)	8538 (5)
1C(9)	3418 (14)	6877 (13)	9078 (7)	2C(9)	−1448 (16)	−3156 (15)	8829 (7)
1C(10)	5128 (15)	7596 (14)	8786 (7)	2C(10)	9834 (16)	−3016 (15)	8147 (8)
1C(11)	3929 (9)	5582 (8)	7244 (4)	2C(11)	8458 (10)	0088 (9)	8216 (5)
1C(12)	4259 (8)	4454 (8)	7215 (4)	2C(12)	7942 (9)	0250 (8)	7616 (4)
1C(13)	3438 (8)	3761 (8)	6934 (4)	2C(13)	8492 (9)	0839 (8)	7338 (4)
1C(14)	3683 (9)	2698 (8)	6896 (4)	2C(14)	8050 (10)	1021 (9)	6770 (5)
1C(15)	4838 (10)	2356 (9)	7165 (5)	2C(15)	7028 (10)	0516 (10)	6490 (5)
1C(16)	5685 (10)	3039 (9)	7447 (5)	2C(16)	6490 (11)	−0096 (10)	6757 (5)
1C(17)	5411 (10)	4111 (9)	7471 (5)	2C(17)	6900 (10)	−0246 (9)	7333 (5)
1C(18)	6344 (11)	4853 (10)	7737 (5)	2C(18)	6283 (12)	−0943 (11)	7618 (6)
1C(19)	2767 (11)	1956 (9)	6590 (5)	2C(19)	8666 (12)	1750 (11)	6490 (6)
1C(20)	2533 (14)	1173 (13)	6974 (7)	2C(20)	8842 (15)	1195 (14)	5905 (7)
1C(21)	3145 (13)	1339 (12)	6063 (6)	2C(21)	7841 (15)	2760 (14)	6397 (7)
1C(22)	1986 (9)	4312 (8)	6152 (4)	2C(22)	9607 (9)	2195 (8)	7925 (4)
1C(23)	0709 (8)	4573 (7)	5960 (4)	2C(23)	0783 (9)	2523 (8)	8119 (4)
1C(24)	0118 (8)	5362 (7)	6245 (4)	2C(24)	1671 (8)	1928 (7)	8441 (4)
1C(25)	−1069 (8)	5614 (8)	6090 (4)	2C(25)	2852 (9)	2140 (8)	8612 (4)
1C(26)	−1722 (10)	5025 (9)	5609 (5)	2C(26)	3151 (11)	3080 (10)	8445 (5)
1C(27)	−1156 (9)	4242 (9)	5317 (4)	2C(27)	2277 (11)	3716 (10)	8141 (5)
1C(28)	0055 (9)	3982 (8)	5476 (4)	2C(28)	1089 (11)	3468 (10)	7965 (5)
1C(29)	0632 (10)	3087 (9)	5152 (5)	2C(29)	0176 (13)	4156 (11)	7604 (6)
1C(30)	−1684 (10)	6488 (9)	6420 (5)	2C(30)	3779 (10)	1407 (9)	8938 (6)
1C(31)	7358 (13)	6026 (12)	6654 (6)	2C(31)	4723 (13)	1007 (12)	8589 (6)
1C(32)	7732 (12)	7348 (11)	6047 (6)	2C(32)	4385 (13)	1977 (12)	9517 (6)
1C(33)	1388 (9)	6683 (8)	6639 (4)	2C(33)	0907 (9)	1021 (8)	9055 (4)

[a] The T superscript denotes the *trans*-stilbene half-molecules in the asymmetric unit. The first figure denotes the TOT molecule of the *trans*-stilbene clathrate.

Irradiation of *cis*-Stilbene·TOT Clathrate. After ca. 4–5 h of irradiation (35 °C) single crystals of *cis*-stilbene·TOT no longer extinguished sharply under the polarizing microscope and had the consistency of an aligned powder which crumbled when lightly pressed. Crystals in which the cis:trans ratio had reached ca. 9:1 were still "single" by microscope observation but at slightly higher ratios of conversion the crystals became powder-like. Powder diffraction spectra revealed stilbene·TOT lines as well as solvent-free·TOT lines; no stilbene lines were present.

When powdered samples of *cis*-stilbene·TOT, taken from the same batch, were irradiated at slightly lower temperatures, the rate of cis → trans isomerization was found to decrease with decreasing temperature (Figure 3). When large (1–2 mg) single crystals were irradiated and not crushed or shaken, the degree of isomerization was always less than that when fresh surfaces were exposed by grinding. Heating of the clathrate in the dark (3 h at 160 °C in a closed tube) did not effect any change. The *trans*-stilbene·TOT clathrate remained totally unchanged when it was irradiated for long periods.

After complete conversion of the 35 °C sample, VPC analysis showed two minor peaks; one, ca. 5% of the *trans*-stilbene peak, was identified as phenanthrene and the second, which emerged from the VPC column between the *cis*- and *trans*-stilbene isomers and comprised about 10% of the *trans*-stilbene peak, was not identified. These two peaks comprised less than 5% of the *trans*-stilbene peak in the −20 °C sample after complete isomerization.

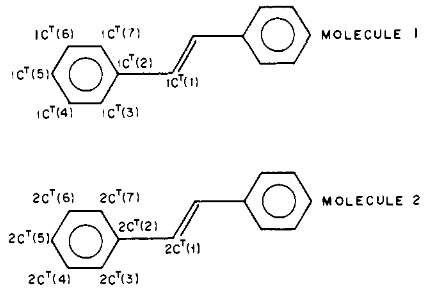

Figure 2. Atom numbering of the two *trans*-stilbene moieties in the *trans*-stilbene·TOT clathrate. The molecules lie on centers of symmetry, molecule 1 on (0, 1/2, 0) and molecule 2 on (1/2, 1/2, 1/2), and therefore only the half-molecules within the asymmetric unit need be numbered.

When an argon-degassed methanolic solution of TOT and *cis*-stilbene was evaporated in a stream of argon and the resulting solid was irradiated without admitting air, the unknown component was not formed. However, phenanthrene was still produced under these conditions.

Iodine-Catalyzed Cis–Trans Isomerization. Samples, in Petri dishes, were placed in desiccators containing several crystals of iodine and protected from light. When *cis*-stilbene·TOT clathrate crystals were

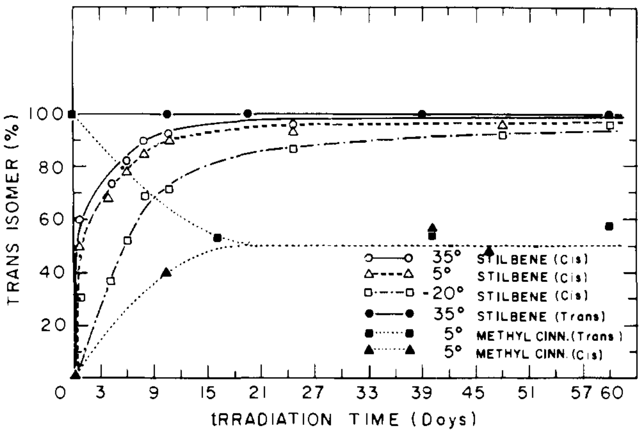

Figure 3. Irradiation of TOT clathrates of *cis*- (▲) and *trans*- (■) methyl cinnamate and *cis*- (○) and *trans*- (●) stilbene. For the irradiation of powdered samples of *cis*-stilbene·TOT clathrate as a function of temperature, the starting samples were taken from the same batch of clathrate. Analyses were performed by gas chromatography and the ratios were calibrated against known mixtures of cis and trans isomers; limits of error ±10%. The phenanthrene formed from the *cis*-stilbene clathrate (see text) has not been included.

exposed at 20 °C, they became brown, and periodic VPC analysis established that cis-trans isomerization was taking place; no volatile products other than *cis*- and *trans*-stilbene were present. Typical values for single uncrushed crystals follow: time of iodine exposure, in days (percent trans isomer), 0 (13%); 5 (20%); 8 (22%); 26 (73); 36 (78%). (The batch of *cis*-stilbene·TOT clathrate crystals used in these experiments had stood exposed to room light and the initial trans isomer in these samples resulted from partial photoisomerization.) When the crystals were powdered, isomerization was more rapid: 0 (13%); 8 (30%); 26 (83%); 36 (100%). Exposure at 5 °C to iodine vapor retarded the isomerization: 0 (11%); 14 (46%); 20 (66%); 26 (67%). When *cis*-stilbene·TOT clathrate samples were exposed to iodine vapor at −20 °C, the crystals remained white and isomerization was completely inhibited. Under the same conditions, *cis*-stilbene (unclathrated) was isomerized more rapidly at 5 °C [0 (5%); 10 (76%); 20 (80%); 30 (97%)] and to an appreciable extent even at −20 °C [0 (5%); 4 (30%)].

Powder diffraction spectra of the *cis*-stilbene·TOT clathrate after iodine-catalyzed isomerization displayed amorphous patterns and contained no lines due to *trans*-stilbene in its own lattice, no TOT·*trans*-stilbene lines, and no TOT·I_2 lines. Exposure of *trans*-stilbene·TOT crystals to iodine vapor caused no detectable isomerization.

Irradiation of Methyl *trans*-Cinnamate·TOT Clathrate. When crystals were irradiated at 35 °C for several days, they developed cracks and no longer appeared single under the microscope. Periodic VPC analysis to establish the isomer ratio showed an initially rapid photoisomerization which reached a steady state after ca. 4 days, comprising ca. 45% cis and 55% trans isomer. The photoisomerization was appreciably slower at 5 °C. No additional VPC peaks were detected.

Irradiation of Methyl *cis*-Cinnamate·TOT Clathrate. VPC analysis of powdered clathrate crystals which had been irradiated at 35 °C showed an increase in the amount of trans isomer; no additional components were found. The "final" distribution of isomers, ca. 50% cis and 50% trans, was reached after 15 days.

When methyl *trans*-cinnamate·TOT clathrate and crystalline methyl *trans*-cinnamate were irradiated under the same conditions, the photoisomerization rate was considerably higher for the clathrate; the ester alone also afforded appreciable dimeric material, no trace of which could be detected from the clathrate.

Results and Discussion

Although cis ⇌ trans photoisomerization of stilbene is very facile in solution,[17] one might have expected that the restricted molecular mobility of the guest species and the rigidity of the TOT clathrate would prevent reaction from taking place in the clathrate.[18] This is indeed the case with the *trans*-stilbene·TOT crystals, which showed essentially no change on irradiation. However, when *cis*-stilbene·TOT crystals were similarly irradiated, photoisomerization to *trans*-stilbene proceeded smoothly; phenanthrene and an additional, presumed oxidation, product were also detected.

Cis ⇌ trans photoisomerization of crystalline olefinic compounds, such as cinnamic acid derivatives, has been studied in the past.[19] In the majority of cases, the crystalline cis isomers are completely converted to the trans isomers and trans → cis isomerization is not observed. (The detailed mechanism of this solid-state reaction is still obscure.[20]) At first sight, the photobehavior of the stilbene·TOT system appears to be similar to that of crystals comprising olefinic molecules. However, if this were so, one might expect that other TOT enclathrated cis olefins would also photoisomerize to the corresponding trans isomer clathrates while the latter would be light stable. We prepared TOT clathrates of the cis and trans isomers of methyl cinnamate and found that for these systems photoisomerization takes place in *both* clathrates. Furthermore, the two cinnamate clathrate crystal structures and the two stilbene clathrates are all isomorphous. The TOT clathrate medium can thus modify the photobehavior of a guest molecule from that observed in solution or in the guest molecule's crystalline phase.

A variety of questions are raised by these observations. To what extent are these TOT clathrates isomorphous and what are the differences, if any, in TOT conformation and in cavity geometry for the different structures? How can isomorphous cavities accommodate molecules as different as *cis*- and *trans*-stilbene? Can the marked molecular discrimination during clathrate formation (overwhelming preference for *trans*- over *cis*-stilbene) be explained and can one suggest reasons for the observed photoreactivity? Does photoisomerization take place within ordered bulk crystal cavities, within deformed cavities, or perhaps outside of the clathrate cavities? In order to help answer these questions and gain a better insight into the factors which control the stability and reactivity of the *trans*-stilbene clathrate and the cinnamate clathrates, respectively, X-ray analyses of the two stilbene clathrates were undertaken.

Crystal Structures of *cis*- and *trans*-Stilbene·TOT Clathrates. Stereodrawings of the *trans*-stilbene·TOT clathrate are presented in Figures 4 and 5. In each unit cell there are four TOT and two stilbene species. For space group $P\bar{1}$, this requires the presence of two independent TOT molecules. The guest molecules in the *trans*-stilbene·TOT clathrate appear in special positions on centers of symmetry, which implies that in each unit cell there are two independent half-molecules of *trans*-stilbene. Although the *cis*-stilbene molecules could not be precisely located, it will be shown later that some conclusions can also be drawn about their positions.

The bond distances and angles of the TOT molecules (listed in the supplementary material) are normal and the molecules have the expected C_3 propeller conformation (cf. Figure 1).[21] This conformation represents one of the rare examples of demonstrated chirality in a molecule of C_3 symmetry;[22] it has also recently been shown that molecules of C_3 symmetry may often act as host species for clathrate formation.[2,23] An idea of the torque of the propeller as well as the degree of deviation from ideal C_3 molecular symmetry can be gained by considering the angles between the normals to the least-squares planes of the phenyl rings in TOT as well as the deviations of dihedral angles in the 12-membered ring. These are listed in Table III. It is clear from the comparison of the TOT molecules in the *trans*-stilbene clathrate with those in the clathrates described thus far and with unsolvated TOT[8-10] that the TOT molecules of *trans*-stilbene clathrate are closest to ideal C_3 molecular symmetry.

Although differing slightly in their conformation, the TOT molecules in the asymmetric unit can be related by a pseudo,

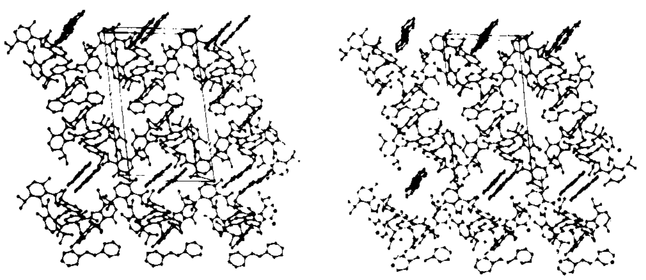

Figure 4. Stereoscopic drawing, made with ORTEP,[45] of the *trans*-stilbene·TOT clathrate structure viewed along the *x* axis. The axial directions are *a* up out of the plane of the paper, *b* →, and *c*↑. Reprinted with permission from ref 3i.

Table III. Maximum Variation of the Angles (deg) Defining the Stereochemistry among the Three Units of TOT in Known Structures

	I[a]	II[a]	III[a]	IV[a]	V[a]
(a,e,i)[b]	3	2.1	10	13	10
(q,u,s)[b]	4.6	0.7	10	10	10
(b,f,j)[b]	11	7	15	20	25
(l,h,d)[b]	3.5	4.7	32	15	12
(t,r,p)[b]	11.5	9.5	15	25	18
(c,k,g)[b]	6.5	3.4	10	10	8
(v,w,x)[c]	3	11	18	16	12

[a] TOT molecule labeled as follows: I and II, TOT in *trans*-stilbene·TOT clathrate; III, TOT in unsolvated TOT (from ref 9 and 10); IV, TOT in a channel complex (from ref 9); V, TOT in a cage complex (from ref 8 and 9). [b] Dihedral angles labeled as follows: (a,e,i), dihedral angle (O_1, C_2, C_1, C_{33}) and its equivalents; (q,u,s), dihedral angle (O_{33}, C_{33}, O_3, C_{24}) and its equivalents; (b,f,j), dihedral angle (C_2, C_1, C_{33}, O_3) and its equivalents; (l,h,d), dihedral angle (C_1, C_2, O_1, C_{11}) and its equivalents; (t,r,p), dihedral angle (C_{24}, C_{23}, C_{22}, O_{22}) and its equivalents; (c,k,g), dihedral angle (C_2, O_1, C_{11}, C_{12}) and its equivalents. [c] (v,w,x) are the angles between the normals to the least-squares planes of the phenyl rings in the TOT molecule.

noncrystallographic symmetry. A least-squares fit program was used in which the parameters defining a symmetry element could be varied in order to minimize the average distances between the atoms of one TOT molecule and the corresponding atoms of the image of the second TOT molecule after the symmetry element had been applied. It was thus found that the two TOT molecules could be related by a pseudoglide plane, the mirror plane being [−2, 0, 1] and the translation (0, ½, 0).

The conformation of the TOT molecules in both the *cis*-stilbene·TOT clathrate and the *trans*-stilbene·TOT clathrate are very much alike. Using a least-squares fit program to define the displacement that would minimize the average distance between TOT molecules of one clathrate and those of the second clathrate if the two structures were superimposed on one another, it was shown that, with respect to a common orthogonal frame defined by (*b*, *b*(*ab*), *ab*), the molecules of both clathrates have nearly the same orientation and that they may be superimposed by translations of less than 0.5 Å alone each coordinate; the main difference lies in the dihedral angles defining the isopropyl group orientation.

The crystallographically independent stilbene molecules lie on centers of symmetry, (0, ½, 0) and (½, ½, ½), respectively, and are located in two perpendicular, noninterconnected channels parallel to the *a* and *b* axes, respectively. The guests and the channels they occupy are clearly seen in the two stereoviews, Figures 4 and 5, of the *trans*-stilbene·TOT structure. In order to better appreciate the relationships between the guests, Figure 6 shows the *trans*-stilbene molecules alone without the surrounding TOT moieties. Although the guest atoms were clearly located on a difference Fourier synthesis, slight orientational disorder does not allow one to draw conclusions about extremely short or long bonds that may occur. The disorder (of a statistical or dynamic nature) which finds its expression in the higher than normal temperature factors of *trans*-stilbene is one of the many possibilities which occur in clathrates. Included molecules may have complete orientational disorder, sometimes detected by a narrow NMR resonance line,[24] or only slightly hindered movement[25] and in these cases they are hardly detectable by X-ray techniques (cf. *cis*-stilbene clathrate, below).

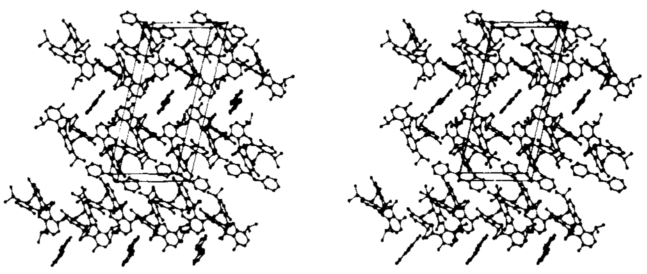

Figure 5. Stereoscopic drawing, made with ORTEP,[45] of the *trans*-stilbene·TOT clathrate structure viewed along the *y* axis. The axial directions are *a* →, *b* down out of the plane of the paper, and *c*↑.

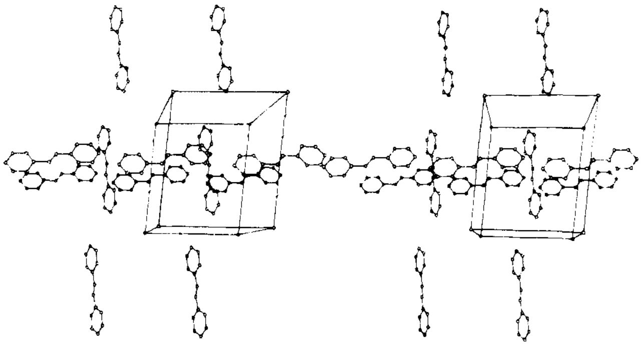

Figure 6. Stereoscopic drawing, made with ORTEP,[45] of the *trans*-stilbene molecules in both channels of the TOT·*trans*-stilbene clathrate. The axial directions are *a* →, *b*↑, and *c* up out of the plane of the paper.

Another feature of the structure deserves comment. Here, as in pure *trans*-stilbene[26a,b] and the related structures of azotoluene[26c] and azobenzene,[26d] the two *trans*-stilbene molecules occupy independent sites in the asymmetric unit. This independence has attracted some interest and, in an elegant experiment of Frank et al.,[27] it was shown that substitution of *trans*-stilbene in its lattice by diphenylmercury occurred preferentially at *one* of the stilbene positions.

The overall packing arrangement of the stilbene molecules, an end-to-end linear arrangement which runs through the crystal, is quite similar in the two channels (Figures 4–6). The differences in the channels and their contents can probably be ascribed to the different lengths of the *a* and *b* axes which define the translation repeat distances between the stilbene guests in the two channels, respectively. For the channel along the longer *b* axis (13.0 Å), the shortest distance between carbon atoms in two adjacent stilbene molecules is 4.60 Å and the planes of adjacent benzene rings in neighboring molecules in the infinite chain are separated by only 0.6 Å. The stilbene molecule centered on (½, ½, ½) as located on the Fourier map displays a deviation from planarity (7° dihedral angle for the C—C=C—C group) which is probably due to partial disorder. A peak of electron density similar to that noted in pure *trans*-stilbene, and attributed to partial occupancy of one of the sites by differently oriented *trans*-stilbene molecules,[26c] is also observed in the *trans*-stilbene·TOT structure; this peak

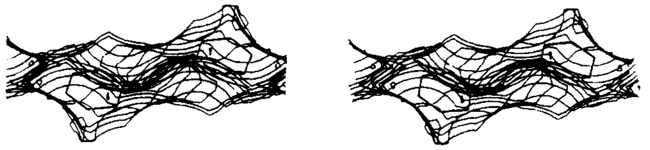

Figure 7. Stereoscopic drawing of the cavity enclosing the *trans*-stilbene (centered on $(0, \frac{1}{2}, 0)$) in the channel parallel to the *a* axis. The contours of the volume accessible to stilbene atoms are drawn in sections separated by 0.40 Å and parallel to the (a,b) plane; they are viewed normal to the (a,b) plane and are included in a parallelepiped defined by $-0.79 \leqslant x \leqslant 0.69$, $0.25 \leqslant y \leqslant 0.75$, $-0.12 \leqslant z \leqslant 0.12$. A point is considered as accessible to stilbene atoms if its distance to the van der Waals envelope of TOT is larger than 1.5 Å.

appears only in the site centered on $(\frac{1}{2}, \frac{1}{2}, \frac{1}{2})$. In the channel along the shorter *a* axis (11.6 Å) the shortest distance between two adjacent stilbene carbon atoms is 3.83 Å and the guests are slightly overlapped, and therefore far from being coplanar; the distance between the planes of adjacent benzene rings in neighboring molecules is 2.0 Å. The molecules in these sites display no disorder or deviation from planarity.

Although peaks of electron density appear in the channels of the *cis*-stilbene·TOT clathrate, the *cis*-stilbene molecules could not be located using conventional least-squares refinement techniques. We believe that this is connected to the centrosymmetric cavities occupied by the guest molecules. Centers of symmetry can only be imposed by orientational disorder and the *cis*-stilbenes must therefore have at least two orientations within the cavities. In addition, it has been shown by VPC analysis that the *cis*-stilbene clathrate has a lower guest occupancy than the *trans*-stilbene clathrate and this, too, imposes statistical disorder.

In order to better visualize the shape and dimensions of the cavities in the crystallographically independent channels, we have represented, in Figures 7 and 8, the contours of the space accessible to guests in the TOT·*trans*-stilbene clathrate. This has been done by subtracting the van der Waals envelope (using published van der Waals radii[28]) of the TOT atoms from the unit cell space; points were then considered as accessible to guest atoms if their distance to any van der Waals envelope of TOT was larger than 1.5 Å. In addition to giving a more concrete representation of TOT-guest interaction, these pictures of free space available to *trans*-stilbene allow one to better understand one of the initially puzzling aspects of the TOT-stilbene system: how can molecules as different in geometry as *cis*- and *trans*-stilbene be accommodated in such closely isomorphous structures? One can see that in both channels of the TOT·*trans*-stilbene clathrate void space remains even when the *trans*-stilbene guest is present and that these "pockets" are located at different positions relative to the guest in the two channels. In the channel parallel to the *a* axis (Figures 4 and 7) the "pockets" are located near the center of symmetry $(0, \frac{1}{2}, 0)$; space appears to be available here for one of the benzene rings of the *cis*-stilbene molecule, the second ring then occupying approximately the same position as one of the benzene rings of *trans*-stilbene. In the channel parallel to the *b* axis (Figures 5 and 8) there is no place for the *cis*-stilbene at the same position as the *trans*-stilbene (i.e., with the double bond close to the $(\frac{1}{2}, \frac{1}{2}, \frac{1}{2})$ center of symmetry). In this channel, there are voids near the ends of the *trans*-stilbene molecules, and one can therefore tentatively locate the *cis*-stilbene molecules of this channel on the $(\frac{1}{2}, 0, \frac{1}{2})$ center of symmetry with one benzene ring in a void pocket and the other one near the position of the benzene rings of *trans*-stilbene. The change of the included molecule in the stilbene·TOT clathrates could a priori require noticeable changes in the shape and volume of both channels, whereas the very similar volume of the unit cell and density in both clathrates indicate that the volume left void by the TOT matrix should not be considerably modified. This is best illustrated in Table IV, where the volumes which are accessible to the guest molecule (defined as above) and the volumes left void by the TOT matrix in both clathrates are given. It is clear that, whereas the volume left void by the TOT matrix does not change by much, the volume accessible to guest atoms undergoes a noticeable change (it grows dramatically in the *b* channel and diminishes in the *a* channel) when passing from the *trans*-stilbene·TOT to the *cis*-stilbene·TOT clathrate. This denotes a change in the shape of the channels, and not in their volumes. Moreover, one can draw, therefrom, a conclusion on the occupancy of both channels in *cis*-stilbene·TOT clathrate. VPC experiments show that therein the guest:host ratio is lower than 1:2; on the basis of the accessible volume calculation we tentatively ascribe the lowest occupancy to the *a* channel.

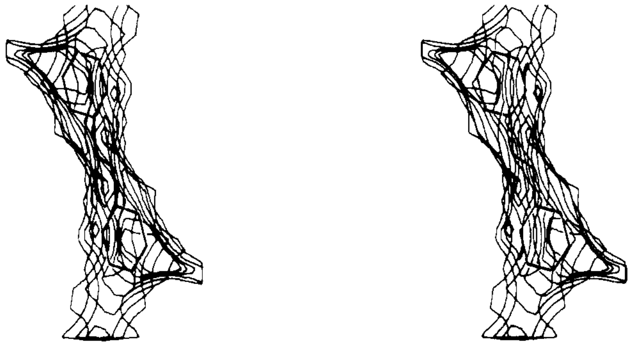

Figure 8. Stereoscopic drawing of cavity enclosing the *trans*-stilbene (centered on $(\frac{1}{2}, \frac{1}{2}, \frac{1}{2})$) in the channel parallel to the *b* axis. The contours of the volume accessible to the stilbene atoms are drawn in sections separated by 0.4 Å and parallel to the (a,b) sections plane; they are viewed normal to the (a,b) plane and are included in a parallelepiped defined by $0.24 \leqslant x \leqslant 0.76$, $0 \leqslant y \leqslant 1$, $0.38 \leqslant z \leqslant 0.62$. A point is considered as accessible to stilbene atoms if its distance to the van der Waals envelope of TOT is larger than 1.5 Å.

Table IV. Volume (Å^3) of the Channels in the *cis*-Stilbene·TOT and *trans*-Stilbene·TOT Clathrates

		volume left void by the TOT matrix	volume accessible to the centers of guest atoms
a channel	*trans*-stilbene·TOT	570	94
	cis-stilbene·TOT	570	72
b channel	*trans*-stilbene·TOT	826	56
	cis-stilbene·TOT	887	103

With regard to the overwhelming preference for *trans*-stilbene over *cis*-stilbene on enclathration with TOT, we believe that this is due in large part to the coincidence of guest symmetry in the former with the cavity symmetry of the host. A noncentrosymmetric guest such as *cis*-stilbene cannot achieve the same favored interactions within the centrosymmetric cavity and is less stable. This proposition, if shown to be general, may have application in the rational choice of molecules which will be preferentially enclathrated by a given host substance. For example, one might expect a host which provides centrosymmetric cavities to preferentially complex with meso (*R*-*S* diastereomer) rather than *dl* (*RR* and *SS*) isomers, and conversely a cavity with a twofold symmetry axis should favor the latter over the former. Crystal symmetry has been exploited in a related way for enriching optical purity by solid-state photodimerization across centrosymmetric pairs of monomers.[29] In the field of clathrate inclusion compounds, rotational disorder of a guest has been observed to occur in order to conform to the imposed cavity symmetry.[30] Although there may be special cases where the noncoincidence of symmetry between guest and host cavity is favored, we feel that, in general, the symmetry matching of guest and host cavity will be a stabilizing influence.

Reaction Pathway. Any solid-state chemical reaction which differs from its solution counterpart raises questions as to how and at what stage the crystalline medium influences the course of the reaction. Thermal solid-state reactions have been formally divided into four stages: an initial loosening or partial unpacking of the molecules at the reaction site, intra- or intermolecular chemical reaction, formation of solid-solution between reactant and product, and, finally, separation of the product phases.[31] Many photochemical solid-state reactions do not require the first stage.

It has been useful to consider solid-state reactions in terms of a model "reaction cavity".[3a] Although the clathrate enclosures represent a concrete and well-defined example of a reaction cavity, reaction therein may differ considerably from reaction within an ordinary molecular crystal. The interactions between guest molecules are greatly weakened owing to the insulating host lattice; the nature of the differences between guest-host interactions as compared to crystalline guest-guest or dissolved guest-solvent interactions are not easily predictable and the way these differences might affect chemical reactivity is even more obscure. In some cases the enclathrated molecule displays selective reactivity[4] and in others inertness[18] and it is of interest to elucidate the factors which control reactivity if one wishes to consider the use of clathrates for selective binding and specific reaction.

In the TOT-mediated photoisomerization reaction, one can envisage an essentially "cage-controlled" process where all molecular change occurs within the clathrate cavity. An alternative view would be that molecules must diffuse out of the closed clathrate cavities into less encumbered locations for reaction to take place and that then, following reaction, a recrystallization step occurs whereby TOT and *trans*-stilbene form the observed product clathrate. Although the latter route cannot be rigorously excluded, we favor, on the basis of our results, a "reaction-in-cavity" pathway.

Powder diffraction spectra before and after the reaction of *cis*-stilbene·TOT to *trans*-stilbene·TOT show that clathrate has been formed and that conversion to a mixture of crystalline TOT and crystalline *trans*-stilbene has not occurred. In addition, at low conversions, up to ca. 10% photoisomerization, the integrity of the host structure is maintained. This may represent the beginning of a single crystal to single crystal transformation which collapses because of the different degree of occupancy in the two clathrates and the small but significant differences in the two clathrate structures. The *cis*-stilbene clathrate is partially empty, whereas the *trans*-stilbene clathrate cavities are fully occupied. As cis → trans isomerization takes place, the empty cavities can congregate and eventually lead to crystallites of guest-free orthorhombic TOT; the powder spectrum of the product indeed shows lines of solvent-free TOT. On the basis of a recent crystal structure of unsolvated Dianin's compound[2] and from Powell's reports of nearly empty TOT clathrate structures (although the latter are metastable with respect to unsolvated TOT),[7b] an empty clathrate need not necessarily collapse, and therefore the stress of different guests and slightly realigned surrounding TOT molecules must also play a role in preventing the existence of all possible proportions of *cis*-stilbene, *trans*-stilbene, and vacant cavities in a clathrate crystal.

In experiments designed to determine whether the *cis*-stilbene clathrate was comprised of guest species in locations where they are easily isomerized, "exposed guests", while other guests were located in sites where they are less subject to isomerization, "unexposed guests", clathrate crystals were treated with iodine vapor, which is known to readily catalyze cis-trans isomerization and has been reported to convert *cis*-stilbene to *trans*-stilbene.[32] *trans*-Stilbene crystals and *trans*-stilbene·TOT clathrate crystals were not affected by exposure to iodine. However, after treatment with iodine at room temperature, the *cis*-stilbene·TOT clathrate was converted to an amorphous-like solid, showing no sharp lines in its powder diagram, containing only TOT and *trans*-stilbene. Iodine-catalyzed isomerization of *cis*-stilbene in TOT clathrate also proceeded at 5 °C. At neither temperature was there any evidence for partial reaction of only some "exposed" *cis*-stilbene molecules; all the guest molecules were converted to *trans*-stilbene.

However, at −20 °C, iodine-catalyzed isomerization of the *cis*-stilbene clathrate does not take place, although unclathrated *cis*-stilbene is smoothly converted to *trans*-stilbene under the same conditions. Photoisomerization of the *cis*-stilbene·TOT clathrate, it will be recalled, proceeds readily at −20 °C (Figure 3). Thus, the *cis*-stilbene·TOT clathrate does not seem to contain molecules in positions, e.g., defects, where iodine-catalyzed isomerization is more facile than in other positions. More evidence should be collected in order to clarify the detailed pathway of the iodine-catalyzed reaction, but it appears that iodine is able to penetrate into and disrupt the clathrate structure. The thermal energy required to achieve this is not available at −20 °C, although isomerization outside of the clathrate can readily be catalyzed at this temperature. From the point of view of the photochemical reaction, these results support the view that enclathrated *cis*-stilbene molecules, and not an equilibrium concentration of "exposed" guests, undergo photoisomerization.

The attainment of a correspondence between cavity site and guest molecular symmetry, noted above, may also be one of the driving forces for the observed reaction. This is supported by the results with the methyl cinnamate isomers, where neither the cis nor the trans molecule can be ordered in the centrosymmetric cavity, and where both isomers undergo photoisomerization in the clathrate. Were it not for these facts one might conclude that the unidirectional cis → trans conversion in the stilbene case is due to the large viscosity effect of the crystalline medium. It has been shown in fluid solution that as viscosity increases the quantum yield for trans → cis photoisomerization of stilbene decreases whereas the cis → trans quantum yield is unchanged.[17] The rigidity of a condensed monomolecular layer also inhibits trans → cis photoisomerization.[33] These results, which have been attributed to the slightly larger molecular volume of the cis isomer,[17,33] may also play a role in the clathrate-mediated isomerization; however, since methyl *cis*-cinnamate can also be expected to have a larger volume than the trans isomer,[34] the viscosity and environmental constraint of the clathrate host structure alone are not adequate to explain the pattern of reactivity. Similarly, the markedly greater thermodynamic stability of *trans*-stilbene over *cis*-stilbene,[37] and the corresponding net contribution to the stability of the *trans*-stilbene clathrate, cannot alone account for the observed photobehavior because methyl *trans*-cinnamate is likewise appreciably more stable than methyl *cis*-cinnamate.[38] We conclude that the transformation of a molecule of $C_1(1)$ symmetry to one of symmetry $C_i(\bar{1})$ within a cavity having $C_i(\bar{1})$ symmetry is a dominant factor in the observed photochemical reactivity. The utilization of such principles may be useful in choosing potential reactants for rationally designed, clathrate-mediated syntheses.

In the description of the crystal structures accommodation of the *cis*-stilbene molecules in the cavities of the *trans*-stilbene·TOT clathrate was rationalized. However, one finds it more difficult to visualize adequate space for the intermediate stage of cis-trans isomerization where one half of the molecule is nearly perpendicular to the other half.[39] For rotation through

180° the cavities, Figures 4, 5, 7, and 8, must be considerably distorted and expanded. Very likely, the often-noted flexibility of TOT[9] (most easily appreciated by handling a molecular model), which is in part responsible for the wide variety of guest structures which may be included, allows sufficient distortion of the cavity, and perhaps of the adjacent cavities, in order to allow rotation about the formal double bond during isomerization. Since the cis-trans photoisomerization of stilbene shows no temperature dependence at the temperature range studied here, the observed temperature dependence of cis-trans isomerization in the *cis*-stilbene·TOT clathrate, Figure 3, can be due to the activation required to sufficiently deform, or "loosen", the surrounding cavity[31] in order to allow the rotation required in the cis-trans isomerization. The disruption of TOT order is not always reversible and, when molecules do not return to their former locations, or when register between movements of TOT molecules in adjacent locations does not occur, single crystal to single crystal transformation cannot be observed and individual crystallites of product phase(s) result.

The degree of involvement and molecular change suffered by the host TOT molecules is not easily examined in the photochemical reactions studied here. However, the chiral properties of TOT, referred to earlier, may perhaps be used to evaluate the degree of TOT involvement and the local, microscopic thermal motion at the reaction site. In a single crystal of one of the TOT clathrates crystallizing in an enantiomorphous space group (not $P\bar{1}$) host molecules of one chirality[7,11] are present. Reaction of guest molecules within such a single crystal, followed by observation of loss of host TOT optical activity (easily measured by solid-state CD[40] or by solution polarimetry[7]), would indicate whether the energy of reaction and TOT thermal motion is adequate to achieve TOT racemization.[21,41]

The cis-trans stilbene isomerization within TOT is accompanied by small amounts of two additional products, phenanthrene and an apparent oxidation product. The latter was absent when irradiation was performed with crystals grown from argon-degassed solutions. Phenanthrene is formed through the photocyclization of *cis*-stilbene to dihydrophenanthrene and subsequent oxidation.[42] The photocyclization step requires far less atomic movement than the predominantly observed photoisomerization reaction and the clathrate cavity would appear to be well suited to enhance photocyclization to dihydrophenanthrene. With some crystals of *cis*-stilbene·TOT clathrate irradiation at −20 °C did cause a yellow coloration which may be attributed to the formation of enclathrated dihydrophenanthrene.[42] However, these observations were not entirely reproducible, nor were we successful in recording good spectra for such irradiated crystals.[43] If dihydrophenanthrene is formed, it must undergo ring opening (thermal or photochemical) at a comparable rate. It is not clear whether ambient oxygen or other oxidizing species promote the oxidation to phenanthrene. Even in clathrate crystals prepared from argon-degassed solutions, phenanthrene was formed. Additional work is clearly called for to corroborate the presence of dihydrophenanthrene and to see whether this species may possibly be isolated in the TOT clathrate cavity.[44]

Conclusion

With the present finding of triclinic, $P\bar{1}$, TOT clathrate inclusion complexes, there have now been described four different possible clathrate structures derived from the same host unit, TOT (trigonal $P3_121$, cage clathrates;[8,9] hexagonal, $P6_1$, channel complexes;[9] monoclinic inclusion complexes[7b]), in addition to the unsolvated orthorhombic $Pna2_1$, modification.[45] The choice of crystal structure is governed primarily if not exclusively by the guest component.

Although solution irradiation of *trans*-stilbene results in a photoequilibrium containing a large excess of the cis isomer, enclathration with TOT results in a light-stable TOT·*trans*-stilbene crystalline complex. The different photoreactivities of *cis*-stilbene·TOT clathrate and of the TOT clathrates of *cis*- and *trans*-methyl cinnamate indicate that clathrate formation can markedly alter the chemical reactivity of a guest molecule from that observed in solution or in the guest's own crystal phase. The observed reactions apparently proceed within the clathrate "reaction cavities". Our results suggest that correlation of guest and host cavity symmetry elements may lead to strongly enhanced clathrate stability as well as provide an element of control over chemical reactivity of guest molecules in clathrate inclusion compounds.

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Supplementary Material Available: Atomic coordinates and thermal parameters of TOT molecules in *cis*-stilbene·TOT clathrate, thermal parameters of atoms in *trans*-stilbene·TOT clathrate, observed and calculated structure factors for the *trans*-stilbene·TOT clathrate, the bond distances and bond angles in the TOT molecules of the *trans*-stilbene·TOT clathrate, and shortest intermolecular contacts in TOT·*trans*-stilbene clathrate (54 pages). Ordering information is given on any current masthead page.

References and Notes

(1) (a) Weizmann Institute of Science; (b) Centre Pharmaceutique.

(2) For a recent general survey and references to previous reviews, see D. D. MacNicol, J. J. McKendrick, and D. R. Wilson, *Chem. Soc. Rev.*, **7**, 65 (1978).

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Photooxygenation of 1,3,5-Cycloheptatriene: Isolation and Characterization of Endoperoxides[1]

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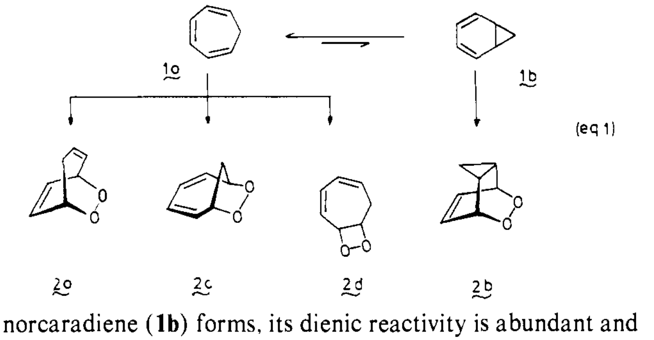
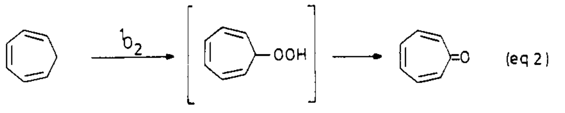
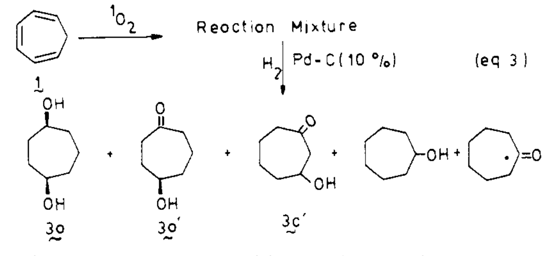
Abstract: The tetraphenylporphyrin-sensitized photooxygenation of 1,3,5-cycloheptatriene at subambient conditions affords the norcaradiene (2+4)-cycloadduct **2b** (3.5%), the tropilidene (2+4)-**2a** (40%) and (2+6)-cycloadducts **2c** (37%), benzaldehyde (5%), and benzene (5%). The characterization of these novel endoperoxides was made on the basis of ^{1}H and ^{13}C NMR spectral data, elemental analyses, diimide reduction to the corresponding saturated cyclic peroxides, and catalytic reduction.

In view of the facile valence isomerization (eq 1)[3] in 1,3,5-cycloheptatriene (**1**) between the tropilidene (**1a**) and norcaradiene (**1b**) forms, its dienic reactivity is abundant and varied. For example, taking singlet oxygen as dienophilic agent for illustration, one may expect formation of the (2+4)-cycloadducts **2a** (tropilidene type) and **2b** (norcaradiene type). However, (2+6)-cycloadducts similar to **2c** are known,[4] and consequently one should expect as well the (2+6)-cycloadduct **2c**. Furthermore, the ability of singlet oxygen to (2+2)-cycloadd is well established,[5] and thus it is possible that the 1,2-dioxetane **2d** might be formed as well. Clearly, 1,3,5-cycloheptatriene is a fascinating substrate for singlet oxygenation.







Indeed, several studies have been reported after Schenck's observation[6] that singlet oxygenation of **1** affords tropone (eq 2) postulated to be derived from the intermediary tropilidene hydroperoxide by dehydration. Thus, Kende and Chu[7] observed a complex product mixture after catalytic hydrogenation of the singlet oxygenated reaction mixture of cycloheptatriene (eq 3). Clearly, reduction products **3a** and **3a′** are derived from the endoperoxide **2a**, the 1,4-diol **3a** by hydrogenolysis of the peroxide linkage and subsequent saturation of the double bonds, and the ketol **3a′** by isomerization of **2a** and subsequent saturation. The ketol **3c′** bespeaks the presence of the unusual (2+6)-endoperoxide **2c**, i.e., isomerization followed by saturation, since otherwise it would be difficult to rationalize the observed substitution pattern. The cycloheptanol and cycloheptanone have a more complex history, probably dehydration followed by saturation of the precursors to **3a**, **3a′**, and **3c**. NMR investigation of the singlet oxygenated

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