DOI: 10.1002/ejoc.200500886

Selective Inclusion of Equatorial Isomers of Cyclohexane-Polyols in Phosphonium Salt Hosts

Koichi Tanaka,*[a] Aki Nakashima[a] Yuji Shimada[a] and Janet L. Scott*[b]

Keywords: Host–guest chemistry / Inclusion complex / Supramolecular chemistry / X-ray structure

Phosphonium salt host compounds **1**–**3** form inclusion crystals with cyclohexane-1,3-diol (**4**), cyclohexane-1,4-diol (**5**) and cyclohexane-1,3,5-triol (**6**), in which the equatorial conformers are selectively included.

Introduction

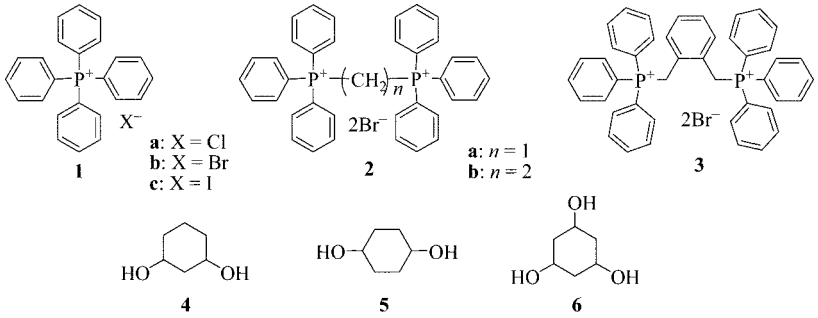
The need to separate mixtures of compounds or isomers resulting from nonselective (or partially selective) synthetic routes has led to the development of a plethora of well-known strategies including fractional distillation, chromatography, selective derivatisation or derivatisation combined with physical separation, to name but a few. Separation strategies that entail the making and breaking of covalent bonds, while often effective, are costly with regard to energy and resources. Hence it is preferable to exploit (relatively) weak, differential intermolecular interactions. Such an approach relies on "molecular recognition" or the formation of energetically favourable assemblies in solution and/or in the solid (usually crystalline) phase.

Enclathration, inclusion complex formation or selective binding to organic receptors may be applied in the separation of mixtures of isomers. Some remarkably complex self-assembling systems that bind specific guests have been described.[1] Supramolecular architectures include capsules[2] (among which are also capsules exhibiting guest-induced assembly[3]), ship-in-bottle structures[4] or cages[5] constructed by metal ion coordination,[6] and guest-specific, multicomponent, hydrogen-bonded molecular boxes.[7] Specific guest binding may provide a route to isomeric separation, particularly if the end product is a crystalline material enriched in one isomeric component of a mixture; however, in many cases, such complex systems are either easily perturbed or simply too costly to apply, and simple, readily accessible and robust host compounds are required to allow such a strategy to be effective.

[a] Department of Applied Chemistry, Faculty of Engineering & High Technology Research Center, Kansai University, Suita, Osaka 564-8680, Japan
Fax: +81-06-6368-0655
E-mail: ktanaka@ipcku.kansai-u.ac.jp
[b] Centre for Green Chemistry, Monash University, Clayton, Victoria 3800, Australia

While there is evidence to suggest that "inclusion resolution" performs poorly, relative to diastereomeric salt formation,[8] in the separation of enantiomeric compounds by crystallization, greater success has been achieved in selective enclathration of geometric or regioisomers. Selective crystallization of one isomer as an inclusion complex and separation of the crystals from the mother liquor followed by destruction of the complex, either by dissolution and selective extraction, or by volatilisation and condensation of the guest (possibly even as a bulk distillation process) provides a direct, noncovalent route to the separation of close isomers. Such selective inclusion or competition has been particularly successfully applied to the separation of isomers of substituted aromatics,[9] including aminobenzonitriles[10] and pyridyl derivatives.[11] Changes in pH have been applied to tune the enclathration of amines,[12] and, in a particularly elegant example, the antibiotic cepharadine, itself synthesized by a selective enclathration process,[13] has been used in the separation of *ortho*- and *para* disubstituted benzene derivatives.[14] Few of these selective inclusion events have been translated into separation processes that make possible the recovery of pure guest molecules on a reasonable scale, although Toda and coworkers have reported some simple-to-apply bulk distillation processes,[15] and host networks (with and without solvent incorporated) that incorporate saturated fatty acids preferentially over those containing unsaturation have been employed in the enrichment of supernatant liquors in the desirable unsaturated fatty acids (as esters).[16]

Separation of *cis* and *trans* isomers of cyclohexane-polyols has been achieved by means such as metal complexation,[17] distillation of boronic acid derivatives[18] or trapping, again through boronate formation, on a resin.[19] Differential binding of *cis*-cyclohexane-1,3-diol and *trans*-cyclohexane-1,4-diol by hosts containing both hydrogen-bond-acceptor and -donor sites has also been reported.[20,21] No recovery of resolved guest was reported in



the latter two cases, and the former require the formation of new co-ordinate or covalent bonds.

Previously, we reported that alkyl- or aryl-substituted phosphonium halides form stable inclusion complexes with various kinds of phenol and naphthol derivatives, and the separation of isomeric phenols can be achieved very efficiently by using inclusion complexation.[22] We have now found that the phosphonium salt host compounds **1**–**3** form inclusion crystals with cyclohexane-1,3-diol (**4**), cyclohexane-1,4-diol (**5**) and cyclohexane-1,3,5-triol (**6**), in which the equatorial conformers are selectively included. X-ray analysis of the inclusion crystals of **1a** and *trans*-**5**, **2b** and *cis*-**4** and **2b** and *cis*,*cis*-**6** showed continuous chains or networks of H-bonded cyclohexanediols and anions (some with water or solvent molecules) bound by tetraphenylphosphonium ions, which in turn interact with each other through a series of CH···π edge-to-face interactions.

Results and Discussion

The inclusion behaviour of host compounds **1**–**3** with cyclohexane-polyols **4**–**6** was studied. Of the tetraphenylphosphonium halides, the chloro and bromo derivatives **1a** and **1b** included the equatorial conformers of cyclohexane-1,4-diol (**5**) and cyclohexane-1,3,5-triol (**6**), respectively, whereas the iodo derivative **1c** showed no inclusion ability. This may be due to the larger steric bulk of the counteranion of **1c** compared to that of **1a** and **1b**. The bis(phosphonium) bromide hosts **2a**, **2b** and **3** also showed equatorial selectivity in inclusion complexation with cyclohexane-1,3-diol (**4**), cyclohexane-1,4-diol (**5**) and cyclohexane-1,3,5-triol (**6**) (Table 1). In a typical example, a solution of **1a** and a 56:44 mixture of *cis*-**5** and *trans*-**5** in EtOH/AcOEt was kept at room temperature for 3 h to give a 1:0.5:1 inclusion complex of **1a**, *trans*-**5** and H_2O as pale yellow prisms. Kugelrohr distillation of the complex in vacuo gave *trans*-**5** (diequatorial conformer) in 98% purity. Similarly, upon inclusion complexation with **1b**, *trans*-**5** was isolated in 96% purity. 1,2-Bis(triphenylphosphonium)ethane bromide (**2b**) included the *cis*-isomer (diequatorial conformer) of cyclohexane-1,3-diol (**4**) to form a crystalline complex. A solution of **2b** and a 53:47 mixture of *cis*-**4** and *trans*-**4** in EtOH/AcOEt was kept at room temperature for 3 h to give a 1:4/3:2 inclusion complex of **2b**, *cis*-**4** and EtOH as colourless prisms. Kugelrohr distillation of the complex in vacuo gave *cis*-**4** in 97% purity. *o*-Phenylenebis(triphenylphosphonium) bromide (**3**) included the *cis*,*cis*-isomer (triequatorial conformer) of cyclohexane-1,3,5-triol (**6**) to form a crystalline complex. A solution of **3** and a 67:33 mixture of *cis*-*cis*-**6** and *cis*-*trans*-**6** in EtOH was kept at room temperature for six days to give a 2:3 inclusion complex of **3** and *cis*,*cis*-**6** as colourless prisms. Kugelrohr distillation of the complex in vacuo gave *cis*,*cis*-**6** in 98% purity. The purity was determined by GC analysis.

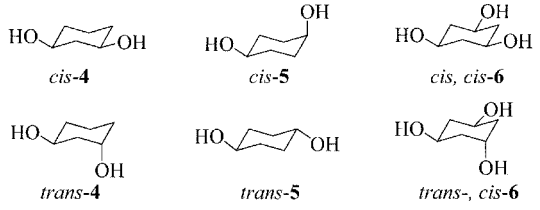


Table 1. The selectivity for *cis*- and *trans* isomers of cyclohexanepolyols.[a]

Guest	1a	1b	1c	2a	2b	3
4	–[b]	–	–	–	*cis* (97%)	–
5	*trans* (98%)	*trans* (96%)	–	–	–	–
6	*cis*,*cis* (97%)	*cis*,*cis* (97%)	–	*cis*,*cis* (96%)	*cis*,*cis* (96%)	*cis*,*cis* (98%)

[a] The *cis*/*trans* selectivity was determined by GC. [b] No complexation.

Crystal structures of **1a** with *trans*-**5** (and water), **2b** with *cis*-**4** (and ethanol), and **2b** with *cis*,*cis*-**6**, designated complex **I**, **II** and **III** respectively, reveal extended hydrogen-bonded networks of the guest cyclohexane-polyols and the halide anions (Figure 1, Figure 2 and Figure 4). All components of complex **I** are well ordered, but complex **II** and **III** exhibit significant disorder. In complex **II**, this disorder is limited to guest components: the asymmetric unit contains 4/3 molecules of *cis*-**4** and two molecules of ethanol, as confirmed by TGA and ^{1}H NMR spectroscopic data. These guests are modelled as two possible chair conformers (C1, C3 and C5 adopting two positions in each case) for cyclohexanediol molecules *A* and *C* (sof = 1) and partial occupancy of a third site by *cis*-**4**, alternatively occupied by two disordered ethanol molecules. The model applied yields chemically sensible molecular structures for each guest, and the stoichiometric ratios of the different molecular species

are reflected in the weight losses measured by TGA, but the guest positions are poorly defined, even at low temperature. The severe disorder detected in guest *cis*-**4** (designated "*B*"), for example, may also be reflected in some substitution of *cis*-**4** for (disordered) ethanol molecules with O atoms O1X and O1Y, thus maintaining the second strand of alternating H-bonded cyclohexanediol (or ethanol) guests and bromide ions. It should be emphasised that the guest is modelled such that the total mass loss due to all guest molecules concurs with the quantity of guest lost on heating (TGA), and is not simply defined by the crystallographic model.

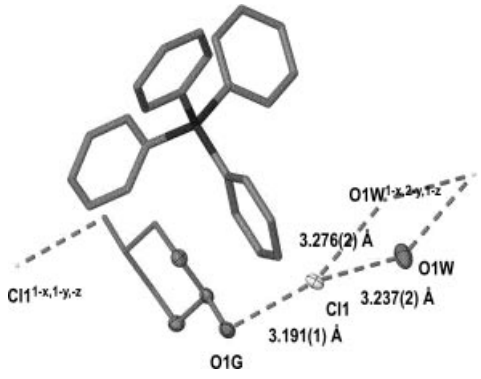


Figure 1. Molecular diagram of **1a**·(*trans*-**5**)$_{0.5}$·H_2O. Hydrogen-bonded chains of *trans*-**5**, chloride and water molecules propagate through the crystal. Guest atoms, the chloride ion and the oxygen atom (water) of the asymmetric unit are presented as ellipsoids at the 50% probability level. Hydrogen-bond geometry: O1G···Cl1; *d* O–H 0.88(3) Å, *d* H···Cl1 2.32(3) Å, ∠ O–H···Cl1 176(2)°; O1W···Cl1$^{x+1,-y+2,-z+1}$; *d* O–H 1.14(4) Å, *d* H···Cl1 2.15(4) Å, ∠ O–H···Cl1 168(3)°; O1W$^{1-x,2-y,1-z}$···Cl1; *d* O–H 1.15(4) Å, *d* H···Cl1 2.12(4) Å, ∠ O–H···Cl1 163(3)°.

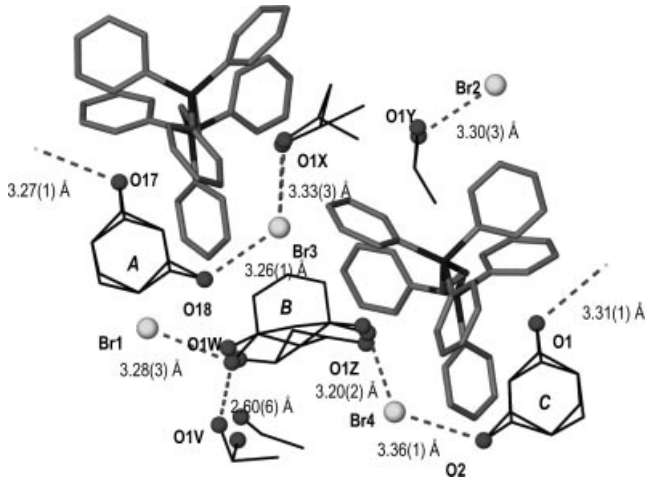


Figure 2. The asymmetric unit of **2b**·(*cis*-**4**)$_{1.33}$·2EtOH contains two independent cations, with disordered bridging CH_2CH_2 groups, and a number of disordered guest molecules (indicated with thin black lines); *cis*-**4** guests *A* and *C* are modelled with full site occupancy while *B* is modelled with sof = 2/3, alternating with (disordered) ethanol molecules. All disordered guests participate in the H-bond network, but, for clarity, only a single H-bond, indicated with a dotted line, is depicted.

Complex **III** exhibits disorder of both phosphonium "host" and cyclohexanetriol guest. Multiple data sets, collected on crystals of good quality, yielded similar results. The choice of the high-symmetry space group $P6_3/mmc$ imposes symmetry constraints that are greater than those of the molecular point group symmetry of both host and guest, implying that the host and the guest are disordered with partial occupancy at all sites. No model with greater Z', in a lower symmetry space group, proved acceptable, and we believe that the current high-symmetry disorder model is the best representation of the structure, as it is both chemically sensible and crystallographically acceptable. The imposed threefold symmetry of both host and guest, is achievable by adoption of multiple positions for the methylene groups, and is combined with disorder over two positions, yielding an averaged dumbbell like shape for the phosphonium dication (Figure 3). *cis*,*cis*-Cyclohexane-1,3,5-triol is modelled over two possible positions, rotated by 60° with regard to each other, and with the non-OH bearing C atoms disordered in up/down fashion (corresponding to the two possible chair conformations with common OH positions) as illustrated in Figure 3.

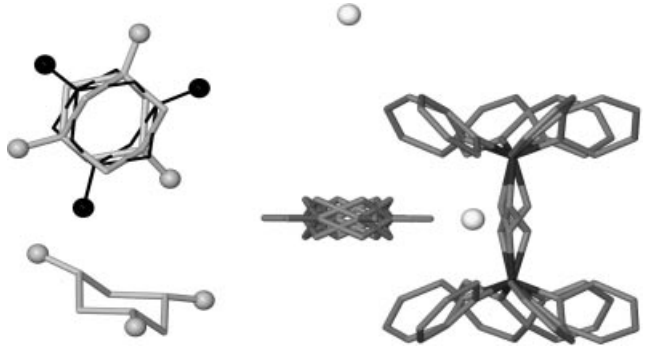


Figure 3. Complex **III** exhibits great disorder, and only non-hydrogen atoms are modelled. The asymmetric unit comprises positions for one $–CH_2–P–C_6H_5$ segment of a phosphonium dication and two Br^- anions. The P atom resides at a special position (1/3, 2/3, *z*) with sof = 1/6; the $-CH_2-$ group is thus disordered over three positions (imposed by space group symmetry) and the C_6H_5 group is disordered over two symmetry-related positions with sof = 1/2 for all atoms including the common atom C2. The guest triol exhibits two rotated positions, thus C–OH groups are arrayed in a hexagonal arrangement and opposite up/down positions (sof = 1/4) for $-CH_2-$ groups corresponding to two possible chair conformers for the *cis*,*cis*- guest in each position (shown in darker and lighter shades at the top left and a single guest position shown in grey at the bottom left).

In all three complexes, guests and anions (and/or water or alcohol solvent) form H-bonded strands (diols), or a network (triol), while 'host' phosphonium cations interact through CH···π and π···π aromatic interactions, forming hydrophobic grids (Figure 4) that are interwoven with the strands of the hydrogen-bonded guests and halide ions.

In complex **III** the host and guest networks are interpenetrating, forming very dense layers of dumbbell-shaped hosts held in the grip of H-bonded guests and anions (Figure 5). Remarkably, the second Br^- anion is not part of the H-bond network and appears in the interlayer, effectively 'pillaring' the dense phosphonium/guest layer, yielding apparently empty channels within the structure, as illustrated

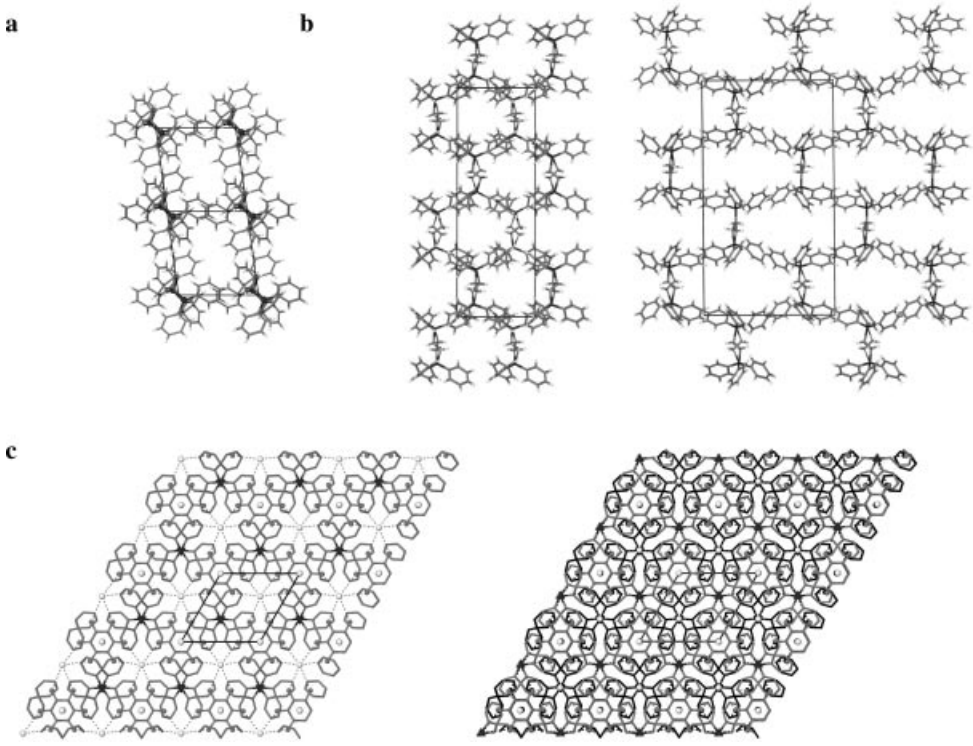


Figure 4. Packing diagrams reveal channels in which H-bonded guest/anion strands are accommodated. a) Complex **I** viewed down [011] (guests and anions removed); b) left, complex **II** viewed down [100] and right, viewed down [010] (guests and anions removed). c) Packing of complex **III** viewed down [001] (Br^- anions and phosphorus and oxygen atoms are depicted as spheres with 0.2 times their van der Waals radii and H-bonds as dotted lines); left, one layer of phosphonium cations with an interwoven network of H-bonded guest triol and Br^- anion [the second Br^- anion on special position (0, 0, 0) is in the interlayer space positioned directly above the disordered cyclohexanetriol] and right, the second layer superimposed on the first (now depicted in black) reflecting the high degree of space group symmetry.

in Figure 5. Data from ^{1}H NMR spectroscopy and TGA do not reveal a second guest (such as the alcohol solvent from which the complex is crystallized), and it is likely that these channels are filled with either gases or disordered, highly labile solvent that is thus rapidly exchanged for gases upon removal of the crystalline complexes from solution.

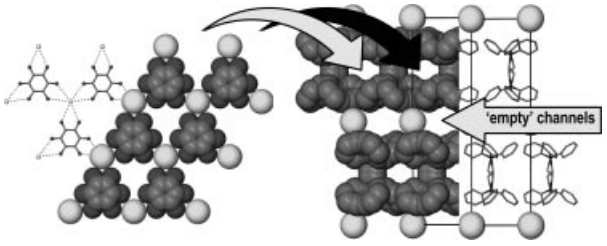


Figure 5. In complex **III** disordered OH groups of the triol are H-bonded to Br^- anions forming a continuous network (d O···Br = 3.438 Å). This network of guest and anion packs such that a dense layer of interpenetrated nets of triol guest with one Br^- anion (depicted viewed down [001] at left) and phosphonium cations are 'pillared' by the second Br^- anion (depicted viewed down [100] at right), leaving apparently 'empty' channels in which no guest molecules are detected – the 1:2 H/G ratio, indicated by ^{1}H NMR spectroscopy and TGA, is satisfied.

While two of the crystal structures are relatively poorly resolved, because of disorder (and, in the case of complex **II**, some crystal twinning), it is clear that the cyclic alcohol guests are firmly hydrogen-bonded, forming part of either extended chains or networks. In all cases, the distance between OH groups (defined by their axial or equatorial disposition in the guest polyol) is critical to maintain the integrity of the H-bond network and thus, in a 'self-healing' system such as a growing crystal, one isomer is overwhelmingly selected. Distillation of the cyclic alcohol from the complex provides a simple method for separation of highly enriched single isomers. The pillared nature of the structure of complex **III** may provide interesting opportunities in sorption/desorption applications, and this is being explored.

Experimental Section

General Remarks: All phosphonium salts **1**–**3** used for the inclusion complexation study are commercially available and were purchased either from Wako chemicals or from Tokyo Kasei Kogyo. ^{1}H NMR spectra were recorded in $CDCl_3$ with a JEOL Lambda 300 instrument. IR spectra were recorded with a JASCO FT-IR 4100 spectrometer. Thermogravimetric analyses were performed with a Rigaku TG-8120 instrument. Gas chromatographic analyses were performed with a Shimadzu GC-2014 instrument by using a SUPELCO α-DEX 120 GC column.

Selective Inclusion of Cyclohexane-1,4-diol (5) in Phosphonium Salt 1a: A solution of **1a** (0.7 g, 1.87 mmol) and a 56:44 mixture of *cis*-**5** and *trans*-**5** (0.43 g, 3.74 mmol) in EtOH/AcOEt (2:7, 4.5 mL)

was kept at room temperature for 3 h to give a 1:0.5:1(H_2O) inclusion complex of **1a** and *trans*-**5** as pale-yellow prisms (0.284 g). Kugelrohr distillation of the complex in vacuo gave *trans*-**5** (0.087 g, 45% yield) in 98% purity. The purity was determined by GC analysis.

Selective Inclusion of Cyclohexane-1,4-diol (5) in Phosphonium Salt 1b: A solution of **1b** (1.83 g, 4.37 mmol) and a 56:44 mixture of *cis*-**5** and *trans*-**5** (1.02 g, 8.75 mmol) in EtOH/AcOEt (3:8, 11 mL) was kept at room temperature for 5 h to give a 1:0.5:1(H_2O) inclusion complex of **1b** and *trans*-**5** as colourless prisms (1.33 g). Kugelrohr distillation of the complex in vacuo gave *trans*-**5** (0.13 g, 28% yield) in 96% purity. The purity was determined by GC analysis.

Selective Inclusion of Cyclohexane-1,3-diol (4) in Phosphonium Salt 2b: A solution of **2b** (0.53 g, 0.75 mmol) and a 53:47 mixture of *cis*-**4** and *trans*-**4** (0.35 g, 3.0 mmol) in EtOH/AcOEt (2:7, 4.5 mL) was kept at room temperature for 3 h to give a 1:4/3:2 inclusion complex of **2b**, *cis*-**4** and EtOH as colourless prisms (0.203 g). Kugelrohr distillation of the complex in vacuo gave *cis*-**4** (0.042 g) in 97% purity. The purity was determined by GC analysis.

Selective inclusion of Cyclohexane-1,3,5-triol (6) in Phosphonium Salt 1a: A solution of **1a** (0.75 g, 2.0 mmol) and a 67:33 mixture of *cis*,*cis*-**6** and *trans*,*cis*-**6** (0.26 g, 2.0 mmol) in EtOH (2 mL) was kept at room temperature for 4 d to give a 3:1 inclusion complex of **1a** and *cis*,*cis*-**6** as colourless prisms (0.464 g). Kugelrohr distillation of the complex in vacuo gave *cis*,*cis*-**6** (0.087 g) in 97% purity. The purity was determined by GC analysis.

Selective Inclusion of Cyclohexane-1,3,5-triol (6) in Phosphonium Salt 1b: A solution of **1b** (0.84 g, 2.0 mmol) and a 67:33 mixture of *cis*,*cis*-**6** and *trans*,*cis*-**6** (0.26 g, 2.0 mmol) in EtOH (2 mL) was kept at room temperature for 4 d to give a 1:1 inclusion complex of **1b** and *cis*,*cis*-**6** as colourless prisms (0.65 g). Kugelrohr distillation of the complex in vacuo gave *cis*,*cis*-**6** (0.065 g) in 97% purity. The purity was determined by GC analysis.

Selective Inclusion of Cyclohexane-1,3,5-triol (6) in Phosphonium Salt 2a: A solution of **2a** (0.488 g, 0.70 mmol) and a 67:33 mixture of *cis*,*cis*-**6** and *trans*,*cis*-**6** (0.185 g, 1.4 mmol) in EtOH (4 mL) was kept at room temperature for 6 d to give a 1:2 inclusion complex of **2a** and *cis*,*cis*-**6** as colourless prisms (0.395 g). Kugelrohr distillation of the complex in vacuo gave *cis*,*cis*-**6** (0.037 g) in 97% purity. The purity was determined by GC analysis.

Selective Inclusion of Cyclohexane-1,3,5-triol (6) in Phosphonium Salt 2b: A solution of **2b** (0.71 g, 1.0 mmol) and a 67:33 mixture of *cis*,*cis*-**6** and *trans*,*cis*-**6** (0.26 g, 2.0 mmol) in EtOH (4 mL) was kept at room temperature for 6 d to give a 1:2 inclusion complex of **2b** and *cis*,*cis*-**6** as colourless prisms (0.61 g). Kugelrohr distillation of the complex in vacuo gave *cis*,*cis*-**6** (0.042 g) in 97% purity. The purity was determined by GC analysis.

Selective inclusion of Cyclohexane-1,3,5-triol (6) in Phosphonium Salt 3: A solution of **3** (0.79 g, 1.0 mmol) and a 67:33 mixture of *cis*,*cis*-**6** and *trans*,*cis*-**6** (0.26 g, 2.0 mmol) in EtOH (4 mL) was kept at room temperature for 6 d to give a 2:3 inclusion complex of **3** and *cis*,*cis*-**6** as colourless prisms (0.823 g). Kugelrohr distillation of the complex in vacuo gave *cis*,*cis*-**6** (0.068 g) in 98% purity. The purity was determined by GC analysis.

X-ray Crystallographic Study: Data were collected with an Enraf–Nonius Kappa CCD diffractometer at 123 K using graphite monochromated Mo-K_α radiation (λ = 0.71073 Å, 1° φ and ω scans). Structures were solved by direct methods with the program SHELXS-97[23] and refined by full-matrix least-squares refinement on F^2 with the programs SHELXL-97[24] and XSeed.[25]

Each of the complexes presented specific crystallographic problems and required different refinement strategies:

Complex I: No disorder was discerned in this structure. All non-hydrogen atoms were refined anisotropically and hydrogen atoms inserted in geometrically determined positions with temperature factors fixed at 1.2 times that of the parent atom.

Crystal Data for 1a·(*trans*-5)$_{0.5}$·H$_2$O: $C_{27}H_{28}ClO_2P$, M_r = 450.91, triclinic, space group $P\bar{1}$, a = 9.2837(2), b = 10.6294(2), c = 13.1612(3) Å, α = 105.053(1), β = 108.885(1), γ = 92.988(1)°, V = 1173.42(4) Å^3, Z = 2, D_{calc} = 1.276 g·cm^{-3}, μ(Mo-K_α) = 0.252 mm^{-1}. Of the 5586 unique reflections measured, 4593 had $I>2\sigma(I)$, R indices [$I>2\sigma(I)$] R_1 = 0.0373, wR_2 = 0.0871, GoF on F^2 = 1.045 for 292 refined parameters and 0 restraints.

Complex II: Guest molecules in this complex exhibited significant disorder, and the final guest occupancy was modelled to match the total quantities of *cis*-**4** and ethanol discerned from TGA and ^{1}H NMR spectroscopic data. Br$^-$ anions and host P atoms were refined anisotropically, as were the linking and *ortho* C atoms of the phenyl rings. P-bridging –CH_2CH_2- groups were refined as disordered over two positions, reflecting a 'pedal-motion' of the 'bar' of this dumbbell-shaped molecule and *cis*-**4** guests *A* and *C* were refined over two positions (with common OH positions), reflecting two possible chair conformers. Disordered guest *cis*-**4** *B* was inserted with partial occupancy (sof = 2/3) alternating with (disordered) ethanol molecules. Hydrogen atoms were inserted in geometrically determined positions with temperature factors fixed at 1.2 times that of the parent atom.

Crystal Data for 2b·(*cis*-4)$_{1.33}$·(C$_2$H$_5$OH)$_2$: $C_{38}H_{34}Br_2P_2$-$(C_6H_{12}O_2)_{1.33}(C_2H_5OH)_2$, M_r = 989.44, monoclinic, space group $P2_1$, a = 16.4096(3), b = 9.9602(2), c = 29.3770(7) Å, α = 90, β = 90.305(1), γ = 90°, V = 4801.4(2) Å^3, Z = 4, D_{calc} = 1.311 g·cm^{-3}, μ(Mo-K_α) = 1.797 mm^{-1}. Of the 35188 reflections measured, 17369 were unique (R_{int} = 0.072), with 8813 $I>2\sigma(I)$. A twin refinement was used and the second twin component was refined to ca. 7% (a number of data sets collected exhibited the characteristics of a racemic twin and the data set with lowest second twin component was chosen as the most suitable). Final refinement was completed with a SWAT card in order to model diffuse solvent (g = 1.12199;U = 3.17249): R indices [$I>2\sigma(I)$] R_1 = 0.1153, wR_2 = 0.2329, GoF on F^2 = 1.012 for 841 refined parameters and 64 restraints (applied to disordered guest molecules).

Complex III: All components of this complex, except for the Br$^-$ anions, exhibited disorder commensurate with higher space group symmetry than molecular symmetry. The asymmetric unit was comprised of only 1/12th of the phosphonium dication and 1/6th of the guest *cis*,*cis*-cyclohexane-1,3,5-triol. Non-hydrogen atoms refined to acceptable positions and all except the threefold disordered bridging -CH_2CH_2- group C atom were refined anisotropically, yielding a chemically and crystallographically reasonable model. No hydrogen atoms were inserted. While the structure is not well-resolved, it is contended that it provides the information sought, i.e. the mode of interaction of host and guest, and the rigid H-bonding network that is almost certainly responsible for the selectivity observed.

Crystal Data for 2b·(*cis*,*cis*-6)$_2$: $C_{38}H_{34}Br_2P_2(C_6H_{12}O_3)_2$, M_r = 976.76, hexagonal, space group $P6_3/mmc$, a = b = 9.7472(2), c = 29.2264(10) Å, α = 90, β = 90, γ = 120°, V = 2404.7(1) Å^3, Z = 2, D_{calc} = 1.349 g·cm^{-3}, μ(Mo-K_α) = 1.796 mm^{-1}. Of the 3086 reflections measured, 979 were unique (R_{int} = 0.049), with 688 $I>2\sigma(I)$. R indices [$I>2\sigma(I)$] R_1 = 0.1598, wR_2 = 0.4746, GoF on F^2 = 2.060 for 72 refined parameters and one restraint (bond length of P–C for bridging ethyl group).

CCDC-271023, CCDC-271024 and CCDC-288896 contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

Acknowledgments

This work was supported by the "High-Tech Research Center" Project for Private Universities: mating fund subsidy from MEXT (Ministry of Education, Culture, Sports, Science and Technology), 2005–2009 and Grants-in Aid for Scientific Research (C), No. 17550109 to K.T. from the Ministry of Education, Culture, Sports, Science and Technology, Japan.

[1] F. Hof, J. Rebek Jr, *PNAS* **2002**, *99*, 4775–4777 and references cited therein.
[2] R. G. Chapman, G. Olovsson, J. Trotter, J. C. Sherman, *J. Am. Chem. Soc.* **1998**, *120*, 6252–6260.
[3] K. Kobayashi, M. Yamanaka, *Chem. Eur. J.* **2005**, *11*, 4725–4734.
[4] T. Kusukawa, M. Fujita, *J. Am. Chem. Soc.* **1999**, *121*, 1397–1398.
[5] T. Kusukawa, M. Fujita, *J. Am. Chem. Soc.* **2002**, *124*, 13576–13582.
[6] M. Fujita, D. Oguro, M. Miyazawa, H. Oka, K. Yamaguchi, K. Ogura, *Nature* **1995**, *378*, 469.
[7] J. M. C. A. Kerckhoffs, M. G. J. ten Cate, M. A. Mateos-Timoneda, F. W. B. van Leeuwen, B. Snellink-Ruël, A. L. Spek, H. Kooijman, M. Crego-Calama, D. N. Reinhoudt, *J. Am. Chem. Soc.* **2005**, *127*, 12697–12708.
[8] S. Müller, M. C. Afraz, R. De Gelder, G. J. A. Ariaans, B. Kaptein, Q. B. Broxterman, A. Bruggink, *Eur. J. Org. Chem.* **2005**, 1082–1096.
[9] L. R. Nassimbeni in *Perspectives in Supramolecular Chemistry* (Eds.: F. Toda, R. Bishop), Wiley, Chichester, **2004**, vol 8, pp. 123–125.
[10] M. R. Caira, L. R. Nassimbeni, F. Toda, D. Vujovic, *J. Am. Chem. Soc.* **2000**, *122*, 9367–9372.
[11] a) S. A. Bourne, K. C. Corin, L. R. Nassimbeni, F. Toda, *Cryst. Growth Des.* **2005**, *5*, 379–382; b) S. Apel, M. Lennartz, L. R. Nassimbeni, E. Weber, *Chem. Eur. J.* **2002**, *8*, 3678–3686; c) L. R. Nassimbeni, H. Su, *Acta Crystallogr., Sect. B* **2001**, *57*, 394–398; M. R. Caira, A. Horne, L. R. Nassimbeni, F. Toda, *J. Mater. Chem.* **1997**, *7*, 2145–2149.
[12] a) S. A. Bourne, K. C. Kirsten, L. R. Nassimbeni, E. Weber, *CrystEngComm* **2004**, *6*, 54–55; b) M. R. Caira, Y. P. Chang, L. R. Nassimbeni, H. Su, *Org. Biomol. Chem.* **2004**, *2*, 655–659.
[13] G. J. Kemperman, J. Zhu, A. J. H. Klunder, B. Zwanenburg, *Eur. J. Org. Chem.* **2001**, 1817–1820.
[14] G. J. Kemperman, R. De Gelder, F. J. Dommerholt, A. J. H. Klunder, B. Zwanenburg, *Eur. J. Org. Chem.* **2002**, 345–350.
[15] Z. Urbancyzk-Lipkowska, F. Toda in *Perspectives in Supramolecular Chemistry* (Eds.: F. Toda, R. Bishop), Wiley, Chichester, **2004**, vol 8, pp. 1–31.
[16] J. N. Voogt, H. W. Blanch, *Biotech. Bioeng.* **2005**, *92*, 532–540.
[17] A. Lehtonen, R. Kivekäs, R. Sillanpää, *Polyhedron* **2002**, *21*, 1133–1138.
[18] R. B. Wetherill, H. C. Brown, G. Zweifel, *J. Org. Chem.* **1962**, *27*, 4708–4709.
[19] E. Seymour, J. M. J. Fréchet, *Tetrahedron Lett.* **1976**, *17*, 3669–3672.
[20] D. A. Bell, S. G. Díaz, V. M. Lynch, E. V. Anslyn, *Tetrahedron Lett.* **1995**, *36*, 4155–4158.
[21] Y. Kikuchi, Y. Tanaka, H. Toi, Y. Aoyama, *J. Am. Chem. Soc.* **1991**, *113*, 1349–1354.
[22] K. Tanaka, F. Toda, "Onium Salt Hosts" in *Comprehensive Supramolecular Chemistry* (Eds.: J. L. Atwood, J. E. D. Davies, D. D. Macnicol, F. Vögtle), vol. 6, ch. 16, pp. 517–534, Pergamon, Oxford, **1996**.
[23] G. M. Sheldrick, *SHELXS-97*, University of Göttingen, **1997**.
[24] G. M. Sheldrick, *SHELXL-97*, University of Göttingen, **1997**.
[25] L. J. Barbour, *J. Supramol. Chem.* **2001**, *1*, 189.

Received: November 11, 2005
Published Online: March 13, 2006

