

Crystalline Complexes of Acyclic *p*-Cresol-Formaldehyde Tetramer with Benzene.
An Induced Fit Type Binding of Benzene Molecule

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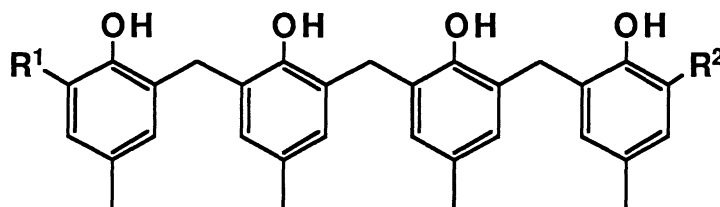
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An acyclic *p*-cresol-formaldehyde tetramer (**1**) has syn-anti arrangement of cresol units and forms "partial cone" type cavity. A benzene is included in the cavity composed of the two facing partial cones. While **1** forms cyclic dimer via intra- and intermolecular hydrogen bondings, its dibromo derivative forms acyclic dimer with anti-anti arrangement of cresol units.

Calixarenes, synthetic macrocycles consisting of oligo-phenols, are known to be able to form inclusion compound with several organic guest molecules.¹⁾ The molecular cavity corresponding to the "cone" shape arrangement of phenols is believed to be responsible for the inclusion property of calixarenes. The corresponding acyclic oligo-phenols may have molecular cavity such as a partial cone which is suitable for inclusion of various small organic compounds, since it is flexible and can change its conformation to accommodate a guest molecule.²⁾ Recently we reported the inclusion properties of acyclic *p*-substituted phenol-formaldehyde oligomers for various organic compounds³⁾ and found *p*-cresol-formaldehyde tetramer (**1**) and its dibromo derivative (**2**)⁴⁾ afforded inclusion complexes only with unsubstituted benzene. No inclusion of mono- or disubstituted benzene such as toluene or xylenes was observed. Different host:guest molar ratio of the two molecular complexes (2:1 in the clathrate of **1** and 1:1 in that of **2**) suggested the different mode of complexation. In this paper we describe X-ray crystallographic analyses⁵⁾ of the inclusion complexes of **1** and **2** with benzene to clarify the details of these interesting phenomena.

Recrystallization of **1** or **2** from benzene solution afforded the stable clathrate in colorless prisms. The crystal data are listed in Table 1. Both crystals belong to triclinic systems with the space group $P\bar{1}$. In the crystal of the complex of **1**, the center of the guest benzene molecule coincides with the crystallographic inversion



- 1** $R^1, R^2 = H$
2 $R^1, R^2 = Br$
3 $R^1 = H, R^2 = Me$

center, thus the crystal has two molecules of **1** and one benzene in a unit cell.

The conformation of the host molecules in these clathrates are shown in Fig. 1. As is clearly seen in this figure these two hosts have different conformation with each other. While the arrangement of the four cresol units in the host molecule of the benzene clathrate of **2** is zigzag type anti-anti fashion, that of **1** is syn-anti. Consequently, the host molecule of the benzene clathrate of **1** forms a "partial cone" like molecular cavity suitable for inclusion of benzene molecule. On the other hand, that for **2** does not have explicit pre-organized molecular cavity suitable for inclusion of small organic molecule. Bulky bromine atoms of two termini of **2** may prevent to have a partial cone type structure. Since the arrangement of the four cresol units of the host molecule itself of **1** without any guest in its crystalline state (clathrand of **1**) was known to be zigzag type⁶⁾ as was found in the benzene clathrate of **2**, significant conformational change has been observed in binding a benzene molecule.

All the intramolecular oxygen-oxygen distances between the two adjacent cresol units in these host molecules are shorter to significant extent than the sum of van der Waals radii of two oxygens. The averaged value in **1** is 2.695 Å and that for **2** is 2.681 Å. These values are very close to that of calix[4]arene itself (2.643 Å)⁷⁾ suggesting the presence of the array of the intramolecular hydrogen bonding between these phenolic OH groups in these host molecules.

The intramolecular hydrogen bonding of the host molecule of benzene clathrate of **1** causes the tilting of the three cresol units with respect to the plane defined by the three oxygen atoms of the A, B, and C rings. The inclination angles of the three cresol units consisting the partial cone type cavity [ring A, B, and C in Fig. 1(a)] are 134°, 133°, and 122°, respectively. The average of the three is somewhat larger than the corresponding value (125°) observed in the calix[4]arene.⁷⁾ Reflecting the larger inclination angle, the interatomic distances between the para position to hydroxy groups are larger [6.243 (ring A and B), 6.125 (ring B and C), and 9.073 Å (ring A and C)] than the corresponding values of the calix[4]arene (5.974 Å and 8.393 Å).⁷⁾

Table 1. Crystal data of the clathrate of **1** and **2** with benzene

1	2
$\text{C}_{31}\text{H}_{32}\text{O}_4 \cdot 1/2(\text{C}_6\text{H}_6)$	$\text{C}_{31}\text{H}_{30}\text{Br}_2\text{O}_4 \cdot \text{C}_6\text{H}_6$
Triclinic $P\bar{1}$	Triclinic $P\bar{1}$
$a=11.719(4)$ Å	$a=11.918(4)$ Å
$b=13.571(4)$	$b=13.535(4)$
$c=9.325(4)$	$c=10.907(5)$
$\alpha=92.31(3)^\circ$	$\alpha=96.77(3)^\circ$
$\beta=105.81(3)$	$\beta=112.28(3)$
$\gamma=99.51(2)$	$\gamma=82.63(3)$
Vol. 1401.6 Å ³	Vol. 1610.0 Å ³
$Z=2$	$Z=2$
$R=0.058$	$R=0.121$

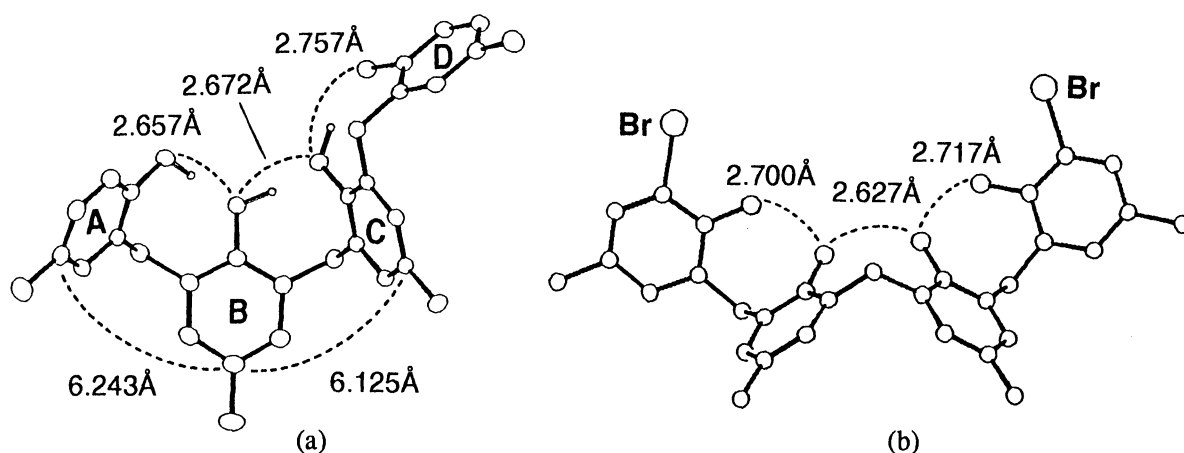


Fig. 1. ORTEP drawings of **1** (a) and **2** (b).

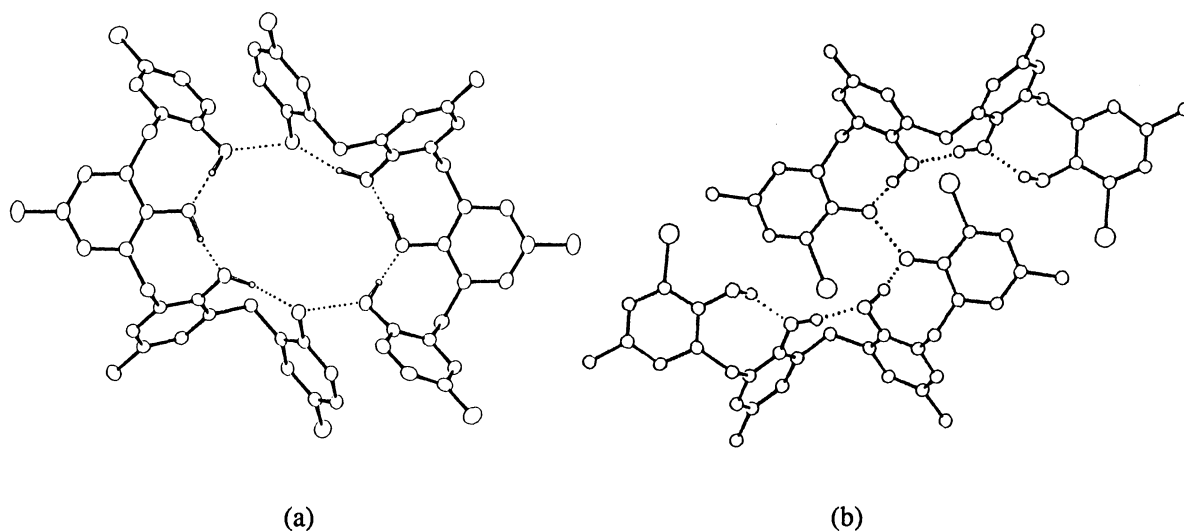


Fig. 2. Dimeric structures of **1** (a) and **2** (b).

The intermolecular hydrogen bonds are also found in each structures, however, the modes are quite different. While the structure of the clathrand of **1** has infinite chains by head-to-head and tail-to-tail hydrogen bonds (the O-O distances are 2.797 and 2.757 Å),⁶⁾ the host molecules in the benzene clathrate of **1** form cyclic dimer by the head-to-tail hydrogen bonding (the O-O distance is 2.719 Å). On the other hand, the host molecule of the benzene clathrate of **2** has a single intermolecular hydrogen bonding at one of the two termini forming acyclic dimer. The intermolecular O-O distance of **2** is somewhat longer than those found in **1**. The formation of the acyclic dimer of **2** by somewhat weak intermolecular hydrogen bonding should be due to the steric hindrance of the bulky bromine atoms flanked on the hydroxy group.

The inclusion modes of the guest molecule in these clathrates are also different with each other. Since the conformation of the host molecule of **2** is zigzag type and has no explicit molecular cavity the lattice void type inclusion was observed in **2**. On the other hand, the guest benzene molecule in the clathrate of **1** was imprisoned by the cage structure composed of two facing partial cone of **1** (Fig. 3). The three cresol rings (A, B, and C) are thus responsible for the incarceration of the host molecule. The remaining fourth cresol ring (D) of the adjacent molecule is located on the open side of the cavity and participates to fix the guest molecule. All the cresol units of the two host molecules of **1** converged to have totally enclosed lattice cage structure. The complex of **1** with benzene can thus be classified as cryptato-clathrate according to the nomenclature proposed by Weber.⁸⁾ The short interatomic C-C contacts of the guest benzene and the host molecule are in between 3.63 Å and 3.80 Å. These relatively short interatomic contacts and relatively small thermal parameters for the carbons of guest benzene suggest that the cavity formed by **1** is exactly the size to include the benzene molecule. This result is in contrast with the similar inclusion complex of **3** with toluene,⁶⁾ in which the guest molecules are disordered.

The present results show interesting phenomena in which the host molecule changes its conformation so as to be suitable for the inclusion of the guest molecule by changing its intra- and intermolecular hydrogen bonding modes. This induced fit⁹⁾ type inclusion behavior in this synthetic host molecule with high flexibility is a good contrast to that in the fixed pre-organized molecular cavity such as calixarenes and cyclodextrins. Further studies on these inclusion phenomena are in progress.

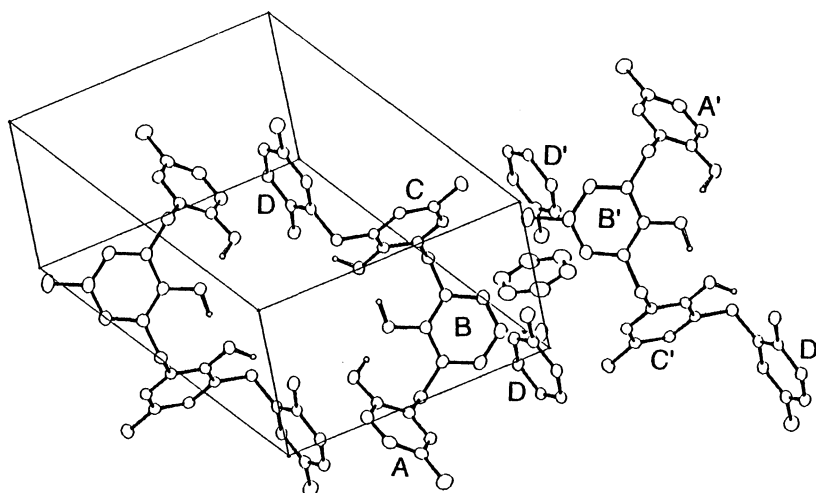


Fig. 3. Crystal structure of the clathrate of **1** with benzene.

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